LOW-TEMPERATURE GEOTHERMAL GROUND WATER

IN THE HOSSTON/COTTON VALLEY HYDROGEOLOGIC UNIT,

FALLS COUNTY AREA, TEXAS

APPROVED:

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LOW-TEMPERATURE GEOTHERMAL GROUND WATER IN THE HOSSTON/COTTON VALLEY HYDROGEOLOGIC UNIT, FALLS COUNTY AREA, TEXAS

BY

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THESIS

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G.L. Macpherson

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ABSTRACT

In the Falls County study area in east-central Texas, the Cotton Valley/Schuler Member and the overlying Hosston Sand (Late Jurassic to Early Cretaceous?) act as a single hydrogeologic unit (aquifer) that contains low-temperature geothermal ground water. The hydrogeologic unit consists of coarse- to very-fine-grained sandstone which becomes more fine-grained to the east, or basinward. Minor amounts of red and black shale are also present, and chert conglomerates become less common basinward. The unit was probably deposited as a bedload-dominated fluvial system in the western part of the study area, as shallow shelf sands or other sand-rich marginal-marine sediments in the central part of the study area, and possibly as sand-rich submarine-fan systems in the eastern part.

Both the depositional history and the Balcones/Ouachita structural hinge control the hydrology of the aquifer. Where Balcones faulting interrupts the continuity of the aquifer, ground-water movement may be channelled along the faults. Transmissivity and hydraulic conductivity are enhanced along the Balcones Fault Zone as well. Where faulting is absent or less evident, transmissivity and hydraulic

conductivity are controlled by net-sand thickness (depositional axes) and ground-water movement is downdip or radially toward a cone of depression centered in McLennan County. This cone of depression, which has resulted from years of ground-water withdrawal, influences ground-water movement throughout most of the meteoric part of the aquifer. In the eastern half of the study area, the ground water in the Hosston/Cotton Valley is saline and the pressure heads are much higher than in the western part of the aquifer, suggesting there is potential for updip movement of the saline ground water. Along the Mexia Fault Zone, which is approximately parallel to and east of the Balcones Fault Zone, pressure heads are somewhat lower than surrounding heads, suggesting that the Fault Zone is the locus of ground-water discharge from the Hosston/Cotton Valley, and possibly from aquifers beneath the Hosston/Cotton Valley.

The Balcones/Ouachita hinge also appears to control the geothermal regime in the study area. In the west, the aquifer overlies Ouachita rocks and is relatively thin. East of the Balcones Fault Zone, where the Ouachita rocks begin to dip steeply into the basin, the aquifer thickens rapidly. These two regions correspond to areas of conductive and forced-convective heat flow, respectively. Geothermal gradients are high (40°C/km) along the Balcones Fault Zone, presumably due to conductive heat flow from the basement rocks, and are probably higher than normal along the Mexia Fault Zone to the east, where the faults may be acting as loci for upwelling ground water.

The water chemistry in the western half of the study area changes from sodium-bicarbonate in the north and sodium-chloride-

sulfate in the south to sodium-sulfate immediately downdip. Farther downdip, the waters become sodium-calcium-chloride and sodium-chloride brines. Stable isotopes ($\delta^{13}C$ and $\delta^{18}O$) indicate a meteoric origin for ground water in the west and water influenced by isotopic exchange in the east. The central part of the study area, where sodium-sulfate waters dominate, is probably an area of mixing of meteoric ground water with hydrogen sulfide moving updip from the basin. The origin of the sodium in these waters is problematical, but some possibilities include alteration of sodic feldspars to clay or dissolution of calcite and subsequent cation-exchange on clays.

The optimum areas for production of low-temperature geothermal ground water are in the western-central part of the area, where water temperatures are fairly low (30°C to 35°C) but water quality is high (dissolved solids of around 1000 mgl^{-1}), and in the central part of the region where temperatures are high (50°C to 60°C) but water quality is generally poor (dissolved solids of more than 3000 mgl^{-1}). In both regions, reinjection of the water after heat extraction is advisable, since the aquifer is presently experiencing a steady decrease in storage.

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INTRODUCTION

Low-temperature geothermal ground water may constitute one of the most widely available energy resources in the United States (Sammel, 1979, p. 91). Low-temperature geothermal water is defined by the U.S. Geological Survey (Sammel, 1979, p. 86-87) as ground water with a temperature less than 90°C but greater than 10°C above mean annual air temperature. A minimum gradient of 30°C/km is required in addition to the above criteria. For purposes of this report, water with a temperature greater than about 32°C is considered thermal (see Appendix I).

In Texas, sedimentary rocks of all ages host low-temperature geothermal aquifers; Cretaceous sandstones along the Balcones/Ouachita trend are especially valuable because they are located along a population trend and the water in them is potable (Woodruff and McBride, 1978). A six-county area in east-central Texas straddling the Balcones/Ouachita hinge served as a study area that exhibits features typical of the larger trend (fig. 1). The Hosston Sand and the adjacent Cotton Valley clastic sediments (presumably Lower Cretaceous and Upper Jurassic) host a low-temperature geothermal resource: ground water produced from the Hosston in the northwestern half of the area is warm (25 to 55°C) and is presently used as a public water supply. The heat produced with the water is usually wasted even though it is a practicable energy resource for direct heating purposes. Two exceptions, the Torbett-Hutchins-Smith (T.H.S.) Memorial Hospital and the

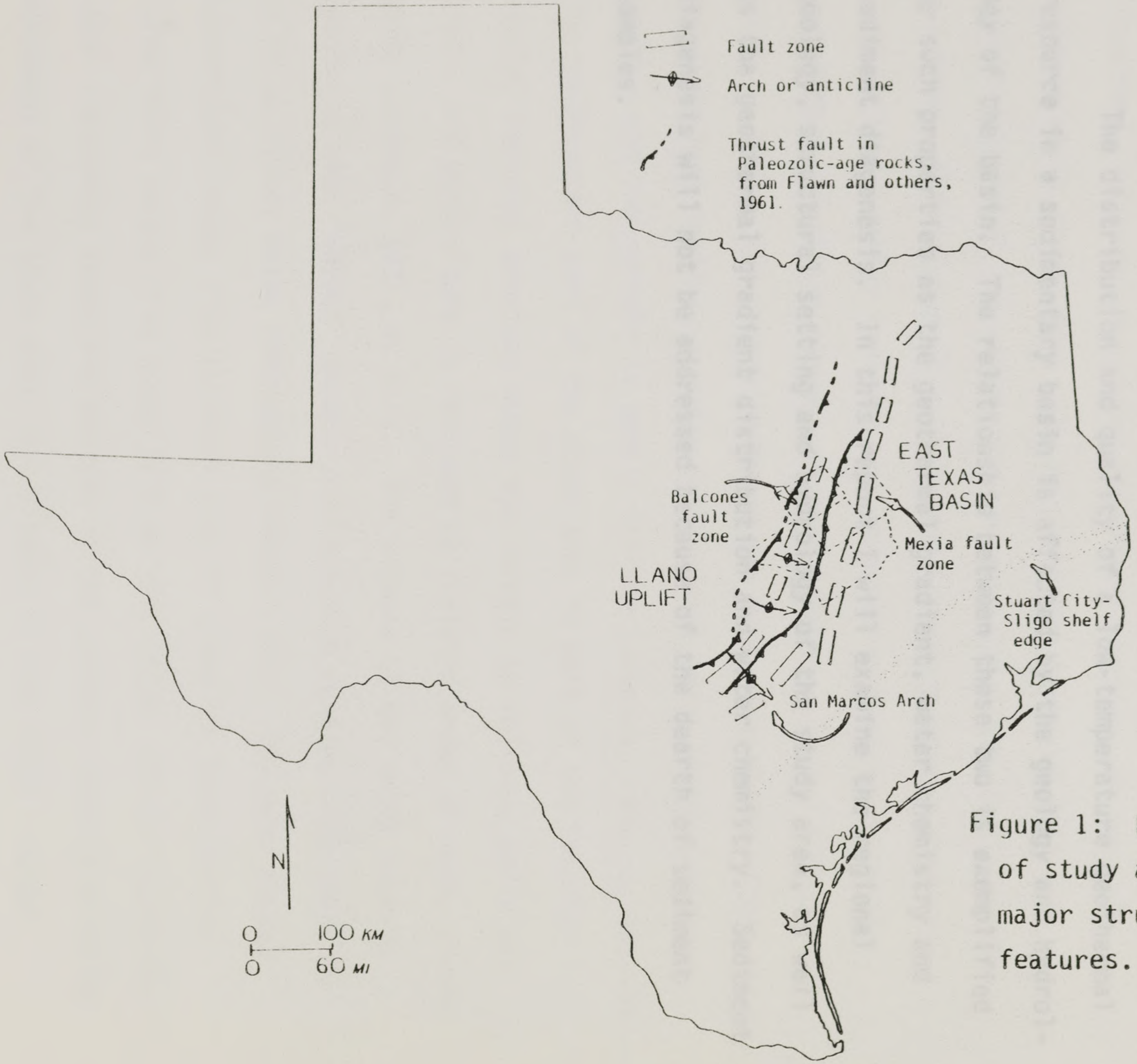


Figure 1: Location of study area and major structural features.

Chamber of Commerce in Marlin, Falls County, are using the water for space heating. Hosston/Cotton Valley water in this area is somewhat warmer than in areas to the north and northwest but is unacceptable as a water supply because the water is brackish.

The distribution and quality of a low-temperature geothermal resource in a sedimentary basin is affected by the geology and hydrology of the basin. The relationship between these two is exemplified by such properties as the geothermal gradient, water chemistry and sediment diagenesis. In this report I will examine the regional geology, structural setting and hydrology of the study area, as well as the geothermal gradient distribution and water chemistry. Sediment diagenesis will not be addressed because of the dearth of sediment samples.

GENERAL DESCRIPTION OF THE STUDY AREA

Climate and Physiography

The Falls County study area (fig. 1) encompasses Bell, Falls, Limestone, McLennan, Milam and Robertson Counties, an area of approximately 14,600 km^2. The northwestern parts of Bell and McLennan Counties lie within the Lampasas Cut Plain physiographic province. This region is a dissected limestone upland characterized by broad-valley lowlands and intervening flat-topped hills and ridges, resistant because of hard limestone layers (Johnson, 1931, p. 125). The central part of the study area falls within the Blackland Prairie, a prime agricultural area, where soils are fertile and the terrain is gently rolling (Johnson, 1931, p. 101-102). The southeastern part of the study area is part of the Interior Coastal Prairies province where the terrain is rolling, soils are sandy, and agriculture is confined to isolated areas of dark, clayey soils (Johnson, 1931, p. 111). The climate of the study area is temperate with "normal" annual precipitation ranging from about 81 to 91 cm (Texas Water Development Board, 1974). The mean annual temperature ranges from about 19°C to 20°C and the mean minimum temperature ranges from about 12°C to 14°C (NOAA, 1981). Where the Lower Cretaceous sands are exposed at the surface, about 8 to 80 km northwest of the study area, the climate is more arid: annual precipitation is 66 to 81 cm (Texas Water Development Board, 1974) and mean annual temperature ranges from 18°C to 19°C (fig. 2). This region is known as the Western Cross Timbers and is characterized by rolling sandy terrain which supports stands of post and blackjack oak (Gould, 1962, p. 10).

The number of heating degree-days in a region is a measure of the practicability of low-temperature geothermal ground water as an energy resource for that region. "...One heating degree-day is given for each degree that the daily mean temperature departs below the base of 65°F (...19°C)" (Huschke, 1959, p. 274). Waco, McLennan County, had 2379 heating degree-days in 1979-80. In contrast, Brownsville in southern Texas had 655 and Wichita Falls in northern Texas had 3055 heating degree-days (NOAA, 1981)(fig. 3). Heating degree-days are used in calculation of energy available from the ground water (Appendix I).

Stratigraphy

The stratigraphy of the Lower Cretaceous and Upper Jurassic is complicated because of depositional fabric, structural dislocations and nomenclatural inconsistency. Because the Jurassic sediments are not exposed at the surface in Texas, correlations and relationships with underlying and overlying sediments are difficult to determine. Figure 4 summarizes the stratigraphy of the two systems, including nomenclature used in the study area by a number of investigators. Boone (1968, p. 9-11) describes the early development of the nomenclature of the Cretaceous units.

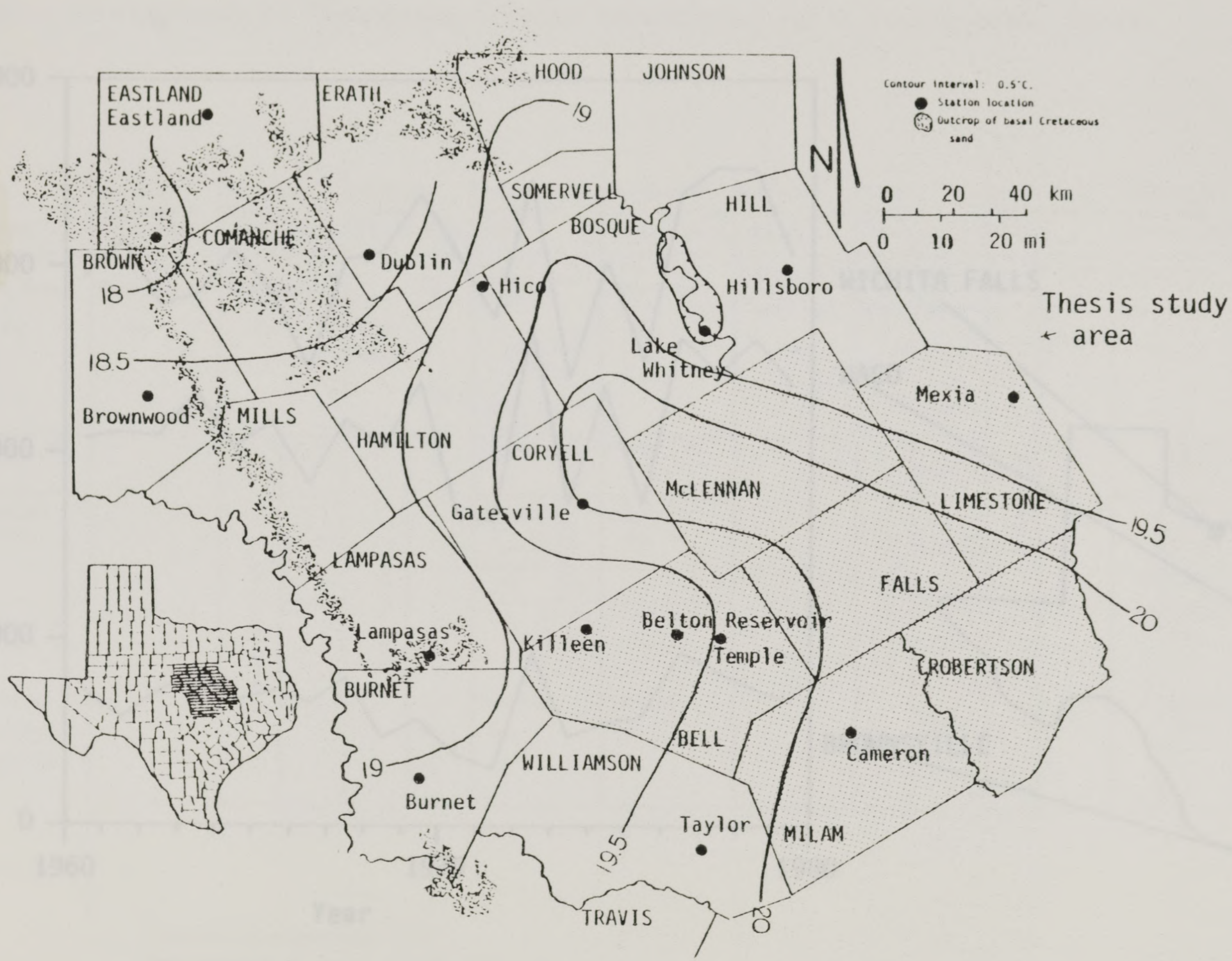


Figure 2: Mean annual air temperature, Falls County study area to outcrop of Lower Cretaceous sands.

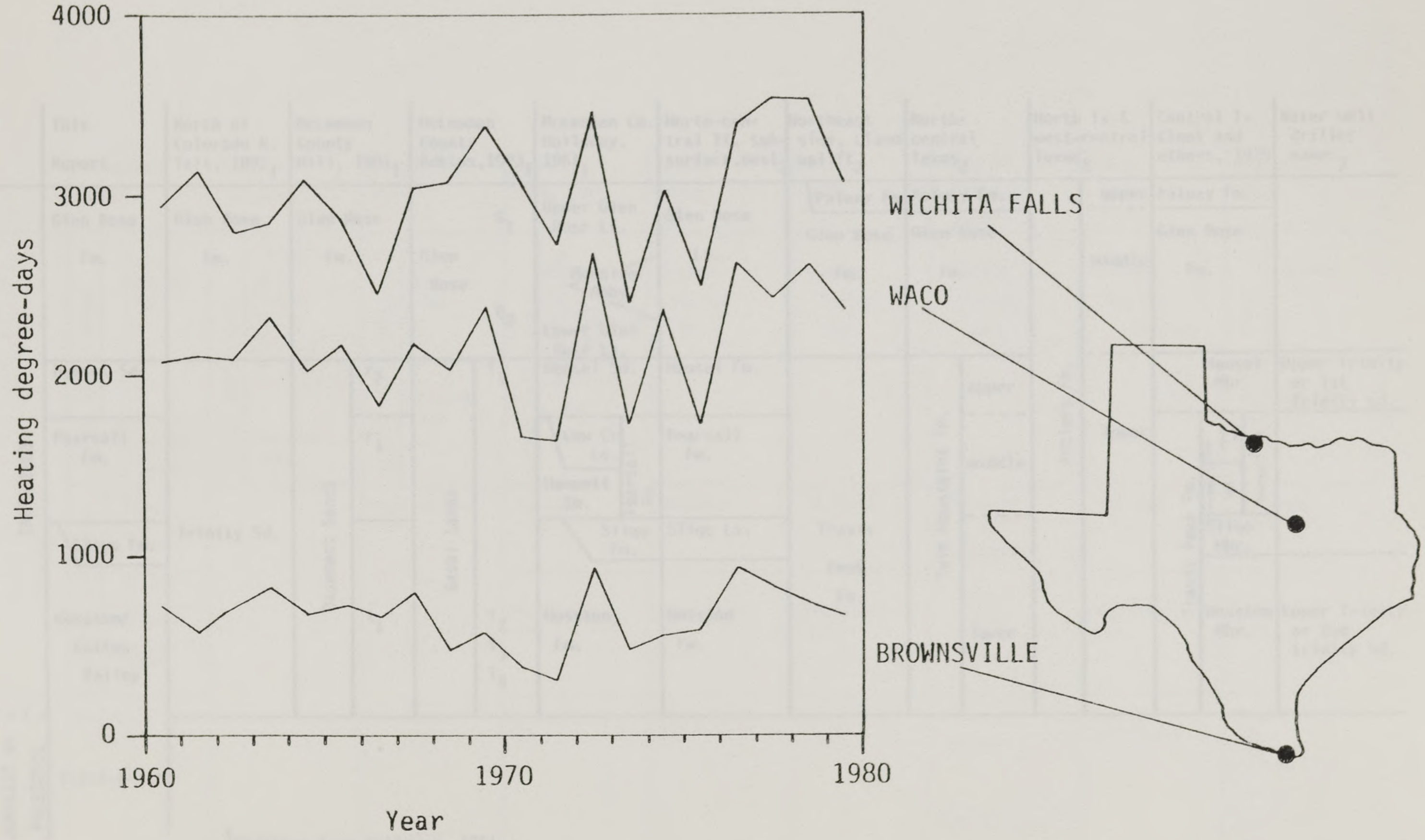


Figure 3: Number of heating degree-days for three cities in Texas.

Figure 4A: Stratigraphy of Cretaceous-Trinity formations, Falls County area, Texas.

	This Report	North of Colorado R. Taft, 1892[1]	McLennan County Hill, 1901[1]	McLennan County Adkins, 1923[1]	McLennan Co. Holloway, 1961[1]	North-central TX, subsurface, east[2]	Northeast side, Llano uplift[2]	North-central Texas[2]	North Tx & west-central Texas[2]	Central Tx Klemt and others, 1975	Water well driller names[3]
CRETACEOUS	Glen Rose Fm.	Glen Rose Fm.	Glen Rose Fm.	Glen Rose; G_1; G_2	Upper Glen Rose Ls.; Massive Anhy.; Lower Glen Rose Ls.	Glen Rose Ls.	Paluxy Fm; Glen Rose Fm.	Paluxy Fm.; Glen Rose Fm.	Antlers Fm.: upper; middle	Paluxy Fm.; Glen Rose Fm.	
	Hensel Sd.	Trinity Sd.	Basement Sands: r_2	Basal Sands: T_1	Hensel Sd.	Hensel Fm.	Travis Peak Fm.	Twin Mountains Fm.: upper	Antlers Fm.: lower	Hensel Mbr.	Upper Trinity or 1st Trinity sd.
	Pearsall Fm.		r_1		Cow Cr Ls.; Hammett Sh. (Pearsall Fm.)	Pearsall Fm.		middle		Travis Peak Fm.: Cow Creek Mbr.; Hammett Mbr.; Pearsall Mbr.	
	Sligo Fm.		t_1		Sligo Fm.	Sligo Ls.				Sligo Mbr.	
	Hosston/ Cotton Valley			T_2 T_3 T_4	Hosston Fm.	Hosston Fm.		lower		Hosston Mbr.	Lower Trinity or 2nd Trinity Sd.
– ? – ? – ? – JURASSIC or PALEOZOIC	?-?-?-?-?-?										

[1]Modified from Holloway, 1961.
[2]Modified from Fisher and Rodda, 1967.
[3]From Klemt and others, 1975.

Figure 4B: Stratigraphy of Jurassic and older formations, Falls County area, Texas.

	Dickenson, 1968	Mann and Thomas, 1964	Forgotson, 1954	Swain, 1944,1949	Imlay, 1943	Weeks, 1930	Todd & Mitchum, 1977	Eaton, 1964	Nichols, 1964
JURASSIC	Cotton Valley Group: Schuler Fm. (Q tongue, P tongue)	Cotton Valley Group: Schuler Fm. (Knowles Ls., Hico Sh., Terry-ville Ss.); Bossier Fm.	Cotton Valley Group: Schuler Fm.; Bossier Fm.	Cotton Valley Group: Schuler Fm. (Dorcheat Mbr., Shongaloo Mbr.); Bossier Fm.	Cotton Valley Fm.	Cotton Valley Fm.	Cotton Valley Group[1]	Cotton Valley Clastics	Cotton Valley Group: Shuler Fm.; Bossier Fm.
JURASSIC	Buckner Fm: Upper; Lower		Haynesville Fm.	Buckner Fm.	Buckner Fm.	Buckner Fm.	Gilmer- Buckner-	Buckner Fm.	Buckner Fm.
JURASSIC	Smackover Fm: Upper; Middle; Lower			Smackover Fm.	Smackover Fm.	Smackover Ls.	Smack-over	Smackover Fm.	Smackover Ls.
TRIASSIC	Norphlet Fm.			Eagle Mills Fm.	Eagle Mills Fm.	Eagle Mills Fm.[2]	Louann-Werner; Eagle Mills	Pre-Smackover	Norphlet Fm.; Louann Salt; Werner Fm.; Eagle Mills Fm.

[1]Cretaceous-Jurassic
[2]Permian?

The principle units of interest for this study are the Sligo Formation, the Hosston Formation or Hosston Sand and the Schuler Formation also known as the upper Cotton Valley or the Cotton Valley clastics. The Sligo Formation was named for the Sligo Field in northeastern Louisiana (Imlay, 1940, p. 33). In the study area it is an oolitic limestone or dolomite and grades laterally into sands and shales in McLennan and Bell Counties. The Hosston Formation is presumably lowermost Cretaceous in age; the name was first applied to basal Cretaceous clastic deposits encountered in wells in northwestern Louisiana (Imlay, 1940, p. 29). Hosston-equivalent strata are exposed at the surface northwest of the study area, where they are known as the Sycamore Sand or the Travis Peak Formation, and have been described by Hill (1901), Bloodworth (1941), Forgotson (1957), Bain (1967), Fisher and Rodda (1967), Boone (1968), Bushaw (1968) and Klemt and others (1975).

The Cotton Valley Group, presumably late Upper Jurassic in age, was first described as the marine fossiliferous dark shale, limestone and sandstone underlying redbeds of the Hosston Formation in the Cotton Valley Field, Webster Parish, Louisiana (Forgotson, 1954, p. 2476). The upper member of the Cotton Valley, the Schuler Formation, is of principle concern in this report. It consists of sandstone, conglomerate, shale and siltstone in the study area, and will be called informally the Cotton Valley.

Lozo and Stricklin (1956, p. 68) used the cyclic nature of the Lower Cretaceous sediments to define subdivisions based on a lower terrigenous phase and an upper carbonate phase. The Sligo and Hosston are such a couplet and they are treated as a unit in this report (along with the underlying Cotton Valley) when examining the structural geology of the study area. The transition between the Sligo and Hosston is gradational and difficult to define precisely whereas the contact between the Sligo and younger formations is generally more abrupt; thus the top of the couplet is easily identified.

Tectonic Setting

The Falls County area is located on the southwestern edge of the East Texas Basin, southeast of and straddling the Ouachita structural belt as defined by Flawn and others (1961) (fig. 1). Throughout most of the Mesozoic, the East Texas Basin was actively subsiding. The Ouachita structural belt served as a hinge between the East Texas Basin and the relatively stable platform to the west (Hayward and Brown, 1967, p. 32). The lowermost Cretaceous sands blanketed the Wichita peneplain (Hill, 1901, p. 363) which had developed on truncated metamorphic rocks of the Ouachita structural belt and unmetamorphosed Paleozoic rocks to the northwest (Boone, 1968, p. 13). The Wichita peneplain exhibited distinct drainage valleys and intervening divides (Boone, 1968; Bain, 1973). The dip of the paleo-surface is about 3 meters per km in the northwest and increases in the region of the Ouachita structural belt to about 47 meters per km (Flawn and others, 1961, Plate 4). In the southeastern part of the study area Paleozoic-age rocks have not been penetrated and overlying geologic units thicken considerably.

Hydrologic Setting

Surface

The study area lies almost entirely within the Brazos River drainage basin (fig. 5). The Brazos River flows south-southeast through central McLennan and Falls Counties. The Leon and Lampasas Rivers, also flowing south-southeast, converge in south-central Bell County to become the Little River, which joins the San Gabriel River in west-central Milam County. The San Gabriel flows to the east to join the Brazos River. The Navasota River flows through west-central and southwestern Limestone County and constitutes the eastern border of Robertson County.

Subsurface

The present Gulf Basin is receiving sediment and parts of it are compacting while other parts are relatively stable (Morton and McGowen, 1980, p. 9), but in general it can be considered a dynamic (geologically active) compacting basin. Compacting basins are characterized by movement of deep fluids from the center of the basin where pore pressures are high toward the fringes or top of the basin where pressures are lower (fig. 6). The shallow meteoric water system and the deep basinal water system are separate and actually

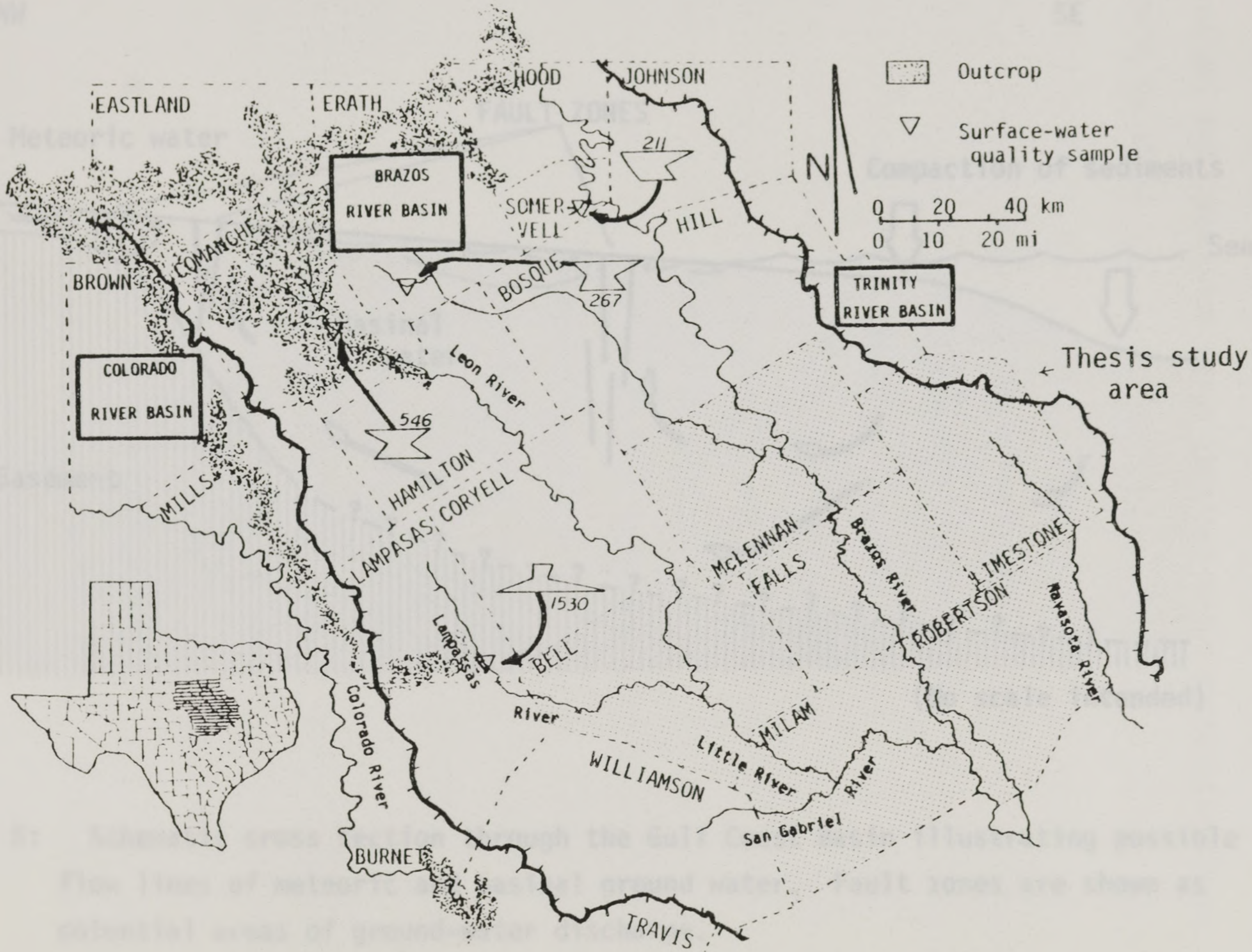


Figure 5: Surface hydrology, Falls County study area to outcrop of Lower Cretaceous sands. Chemical quality of surface water is represented by Stiff diagrams (see section on Water Chemistry); total dissolved solids value shown in mgl^{-1}.

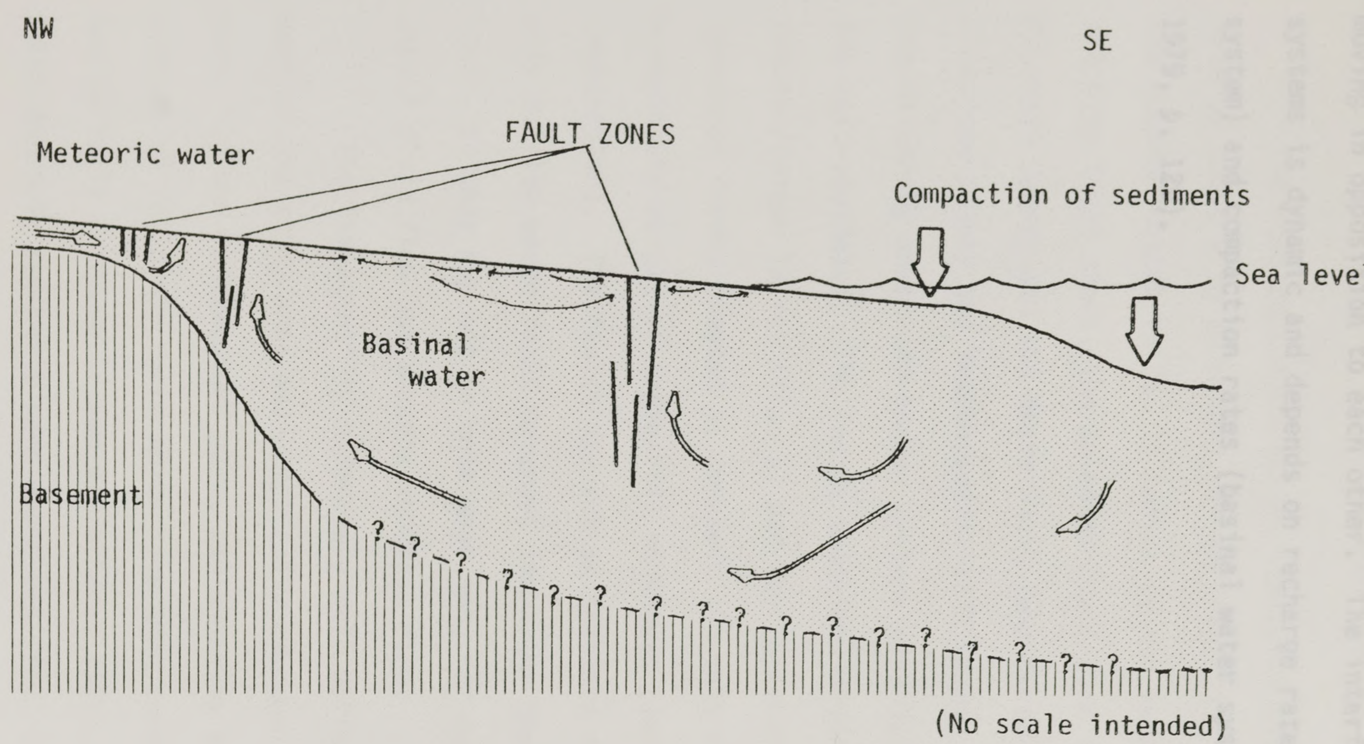


Figure 6: Schematic cross section through the Gulf Coast Basin illustrating possible flow lines of meteoric and basinal ground water. Fault zones are shown as potential areas of ground-water discharge.

moving in opposition to each other. The interface between the two systems is dynamic and depends on recharge rates (meteoric water system) and compaction rates (basinal water system)(Kreitler, 1979, p. 129).

STRUCTURAL GEOLOGY

The Hosston/Cotton Valley sediments dip east-southeast at a rate of about 9 to 30 meters per km (fig. 7). In the study area, the Hosston/Cotton Valley is broken by two major northeast-southwest trending fault zones, the Balcones Fault Zone in south-central McLennan County and the Mexia Fault Zone further east in central Limestone County and southeastern Falls County. Both systems are predominantly horst-and-graben systems with net displacement down to the east-southeast. The faults sometimes extend to the base of the Hosston/Cotton Valley (fig. 8) and may represent adjustment to tensional forces created as Jurassic (?) salt flowed plastically beneath the weight of basin-fill sediments (Jackson and Wilson, in preparation). The faults may act as barriers to fluid flow or as aids to flow where fault movement increases the permeability of the rocks, or they may act in both ways and, for example, inhibit horizontal fluid flow but enhance vertical flow.

The "basement" is moderately well defined in the northwestern part of the study area and practically unknown in the southeastern part. In the northwestern part, the Ouachita structural belt, consisting of Paleozoic rocks which have been thrust to the northwest and variably deformed (Flawn and others, 1961), is the basement on which Mesozoic sediments were deposited (fig. 1). The downdip extent of Paleozoic rocks (fig. 8) suggests that there may have been an embayment in the rocks inherited from earlier times or that this

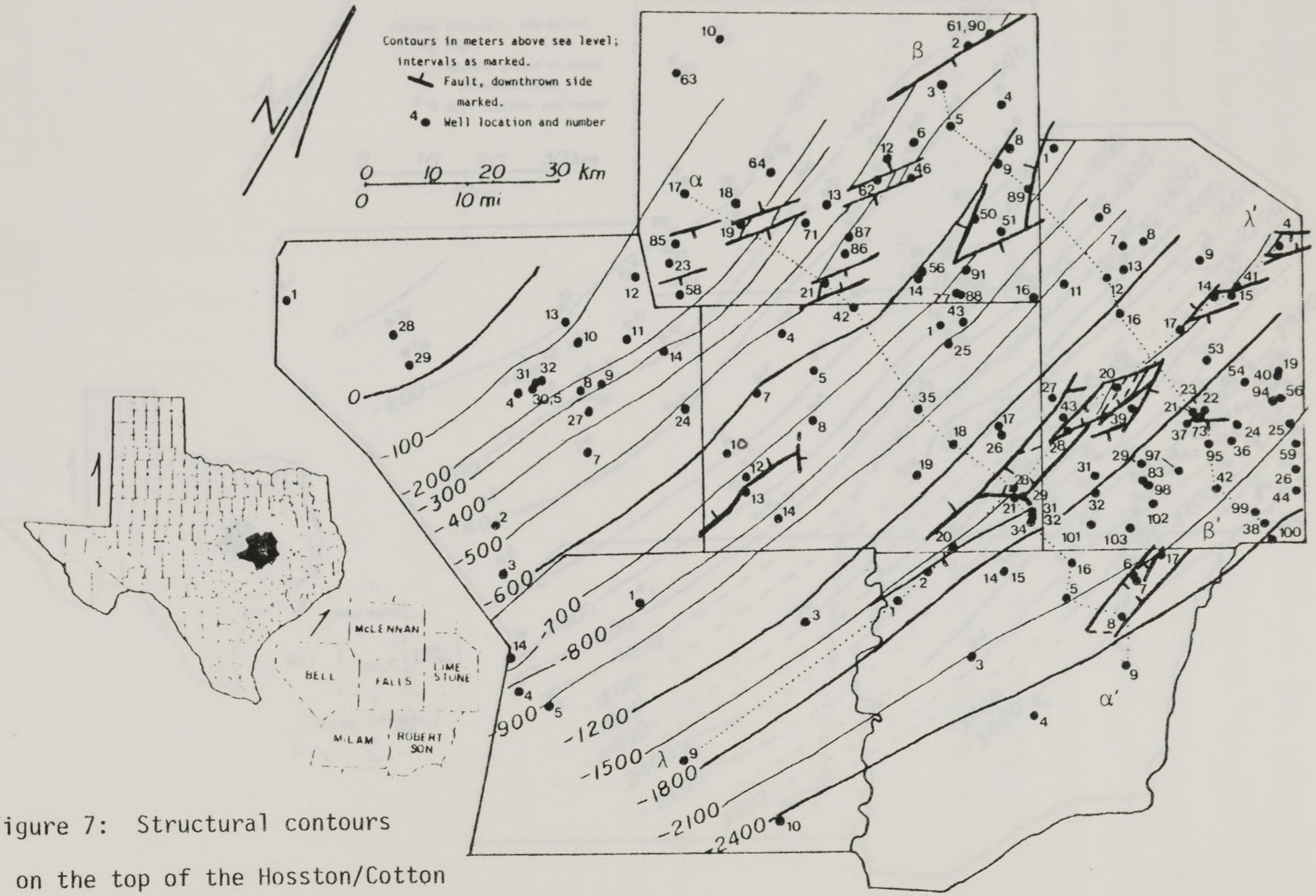


Figure 7: Structural contours on the top of the Hosston/Cotton Valley hydrogeologic unit. Location of cross sections shown as dotted lines. The contour interval is larger in the eastern half of the area, reflecting the steeper dip.

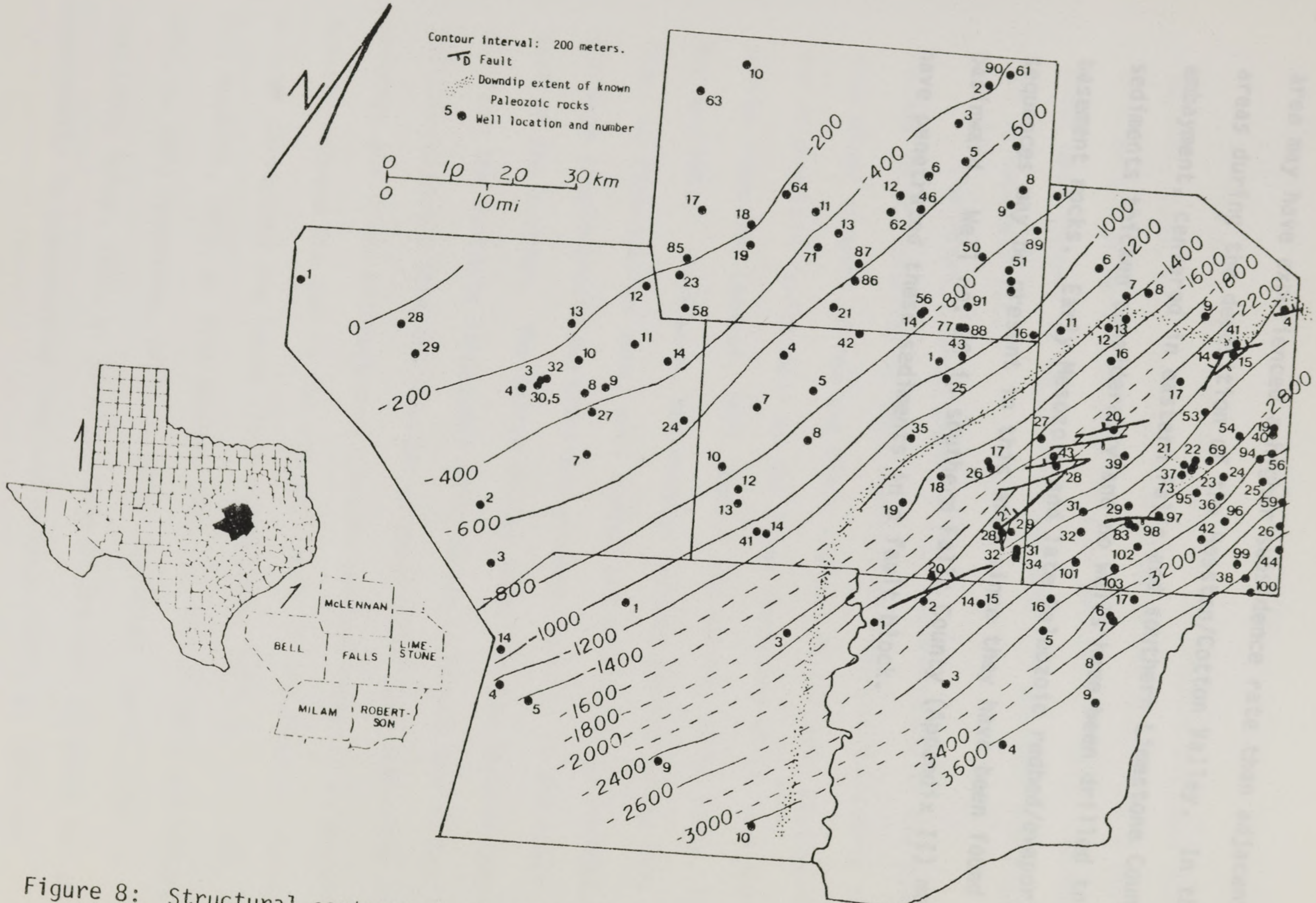


Figure 8: Structural contours on the base of the Hosston/Cotton Valley hydrogeologic unit.

area may have experienced a higher subsidence rate than adjacent areas during the deposition of the Hosston/Cotton Valley. In the embayment, centered in eastern Falls and southern Limestone Counties, sediments thicken considerably and no wells have been drilled to basement rocks. Early Mesozoic and late Paleozoic redbed/evaporite sequences may be present in this area since they have been found basinward. Well no. 20 in southern Falls County (Appendix II) may have penetrated these sediments in a fault block.

SEDIMENTATION

The data base for this part of the project includes 161 geophysical logs, well cuttings from 20 wells and cores from 3 wells. Driller's logs were also examined when available. Basic information about well control is included in Appendix II; sediment descriptions are in Appendix III.

The Hosston Sand, where it lies unconformably on the Ouachita facies rocks, consists of conglomeratic to fine-grained quartz sand with minor amounts of red and black shale. It thickens basinward, and is overlain conformably by the Sligo Formation which is a shallow marine limestone (Bebout, 1977; Bebout and others, 1981; Young, 1967; Murray, 1961). Basinward, the Hosston becomes predominantly very fine- to fine-grained sand, well sorted and subangular to rounded, although conglomeratic horizons are evident, usually in the lower part of the section. The Cotton Valley underlies the Hosston downdip from the Ouachita structural belt; these sediments are virtually indistinguishable from the Hosston on geophysical logs and often in cuttings and core, although many authors contend there is an unconformity between the two in the proximal parts of the Mesozoic basin, or even throughout the basin (Todd and Mitchum, 1977, p. 146, 150, 153; Newkirk, 1971, p. 935; Bushaw, 1968, p. 417; Nichols and others, 1968, p. 988; Forgotson, 1954, p. 2490, 2497-2498; Swain, 1949, p. 1248-1250; Imlay, 1943, p. 65-67). Some of the best evidence for an unconformity is presented by Todd and Mitchum (1977, p. 153) who state that planktonic microfossils in the Sligo and Cotton Valley in South Texas "...indicate a substantial time break at the sequence boundary between the Sligo and Cotton Valley" and that "the upper part of the Cotton Valley is not late Jurassic but early Cretaceous ...in age...." Unfortunately, these statements are not well supported. Evidence by other authors is based primarily on the existence of conglomerates in the basal Hosston, or rather that basal Hosston is defined by conglomerates that indicate an unconformity. Only two of the sets of well cuttings have complete coverage through the Hosston/Cotton Valley sediments. The Milam County no. 3 well, however, penetrates only the thin edge of possible Cotton Valley sediments on the Ouachita rocks. Falls County no. 32 penetrates a thicker section, and several conglomeratic layers were logged. There was no distinct change in color, size or type of sediment that might indicate an unconformity, other than the conglomeratic horizons. Because the purpose of this report is to describe the geothermal resource produced from these sediments, the presence or absence of an unconformity, although geologically significant, is hydrologically unimportant. In fact, the lack of a distinct lithologic difference between the Hosston and Cotton Valley sediments, as well as absence of an aquitard or aquiclude between the two, permits the definition of these as a hydrogeologic unit. Toth (1978, p. 807) defines a hydrogeologic unit as "...a single stratum or combination of strata that function in bulk as either a water-bearing or a water-retarding rock complex relative to adjacent strata." The Hosston and Cotton Valley, in all probability, do act as a single hydrogeologic unit, and are treated as such in this report. It is important to note that these are also treated as a geologic unit, the reasons for which will be made clear below.

The Sligo Formation is not considered part of the hydrogeologic unit because it is thin relative to the Hosston/Cotton Valley and only locally permeable. It is clearly the capping transgressive member of the Hosston-Sligo couplet, as mentioned above, and although the contact between the two is gradational, it is possible to distinguish the Sligo limestone unit from the limey sands and thin limestones which here are considered part of the upper Hosston. The Sligo Formation and the overlying Pearsall Formation probably act as a low-permeability barrier to fluid flow in the study area, and so establish the upper boundary for the hydrogeologic unit. The Bossier Formation, the older member of the Cotton Valley Group, consists predominantly of shale and acts as an aquitard, and so defines the lower limit of the hydrogeologic unit. Where the Bossier is absent, the underlying Buckner Formation also acts as an aquitard, and thus is locally the base of the Hosston/Cotton Valley hydrogeologic unit.

Cross sections through the study area illustrate the relationships described above. The dip sections (figs. 9-10) show the basinward thickening of the hydrogeologic unit and the structural disruptions in the Balcones and Mexia Fault Zones. The strike section (fig. 11) demonstrates the complexity of the Mexia Fault Zone, which is certainly

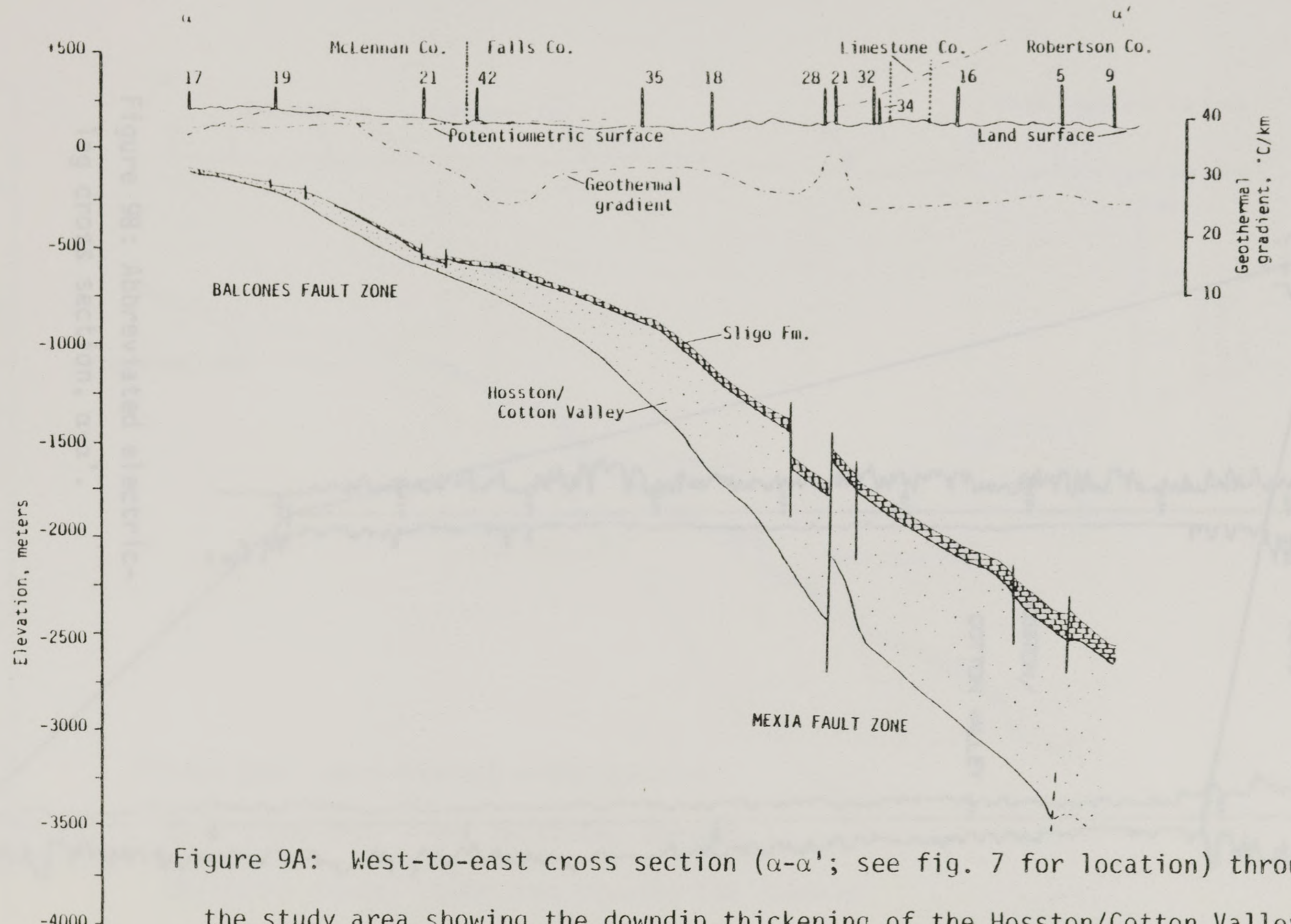


Figure 9A: West-to-east cross section (α-α'; see fig. 7 for location) through the study area showing the downdip thickening of the Hosston/Cotton Valley, major fault zones, and high geothermal gradients near the fault zones. The potentiometric surface is much higher than the land surface in the eastern part of the study area. Well control is shown at the land surface.

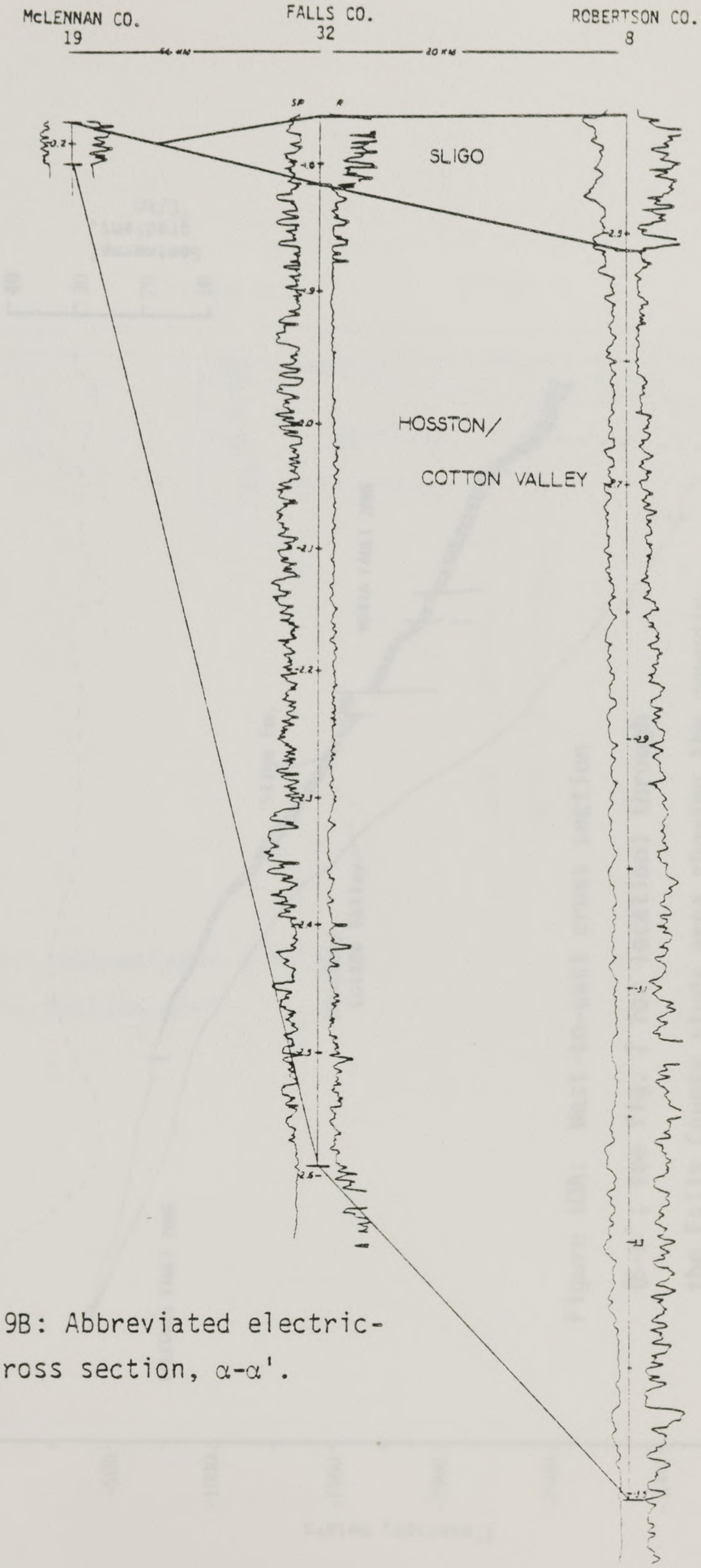


Figure 9B: Abbreviated electric-log cross section, α-α'.

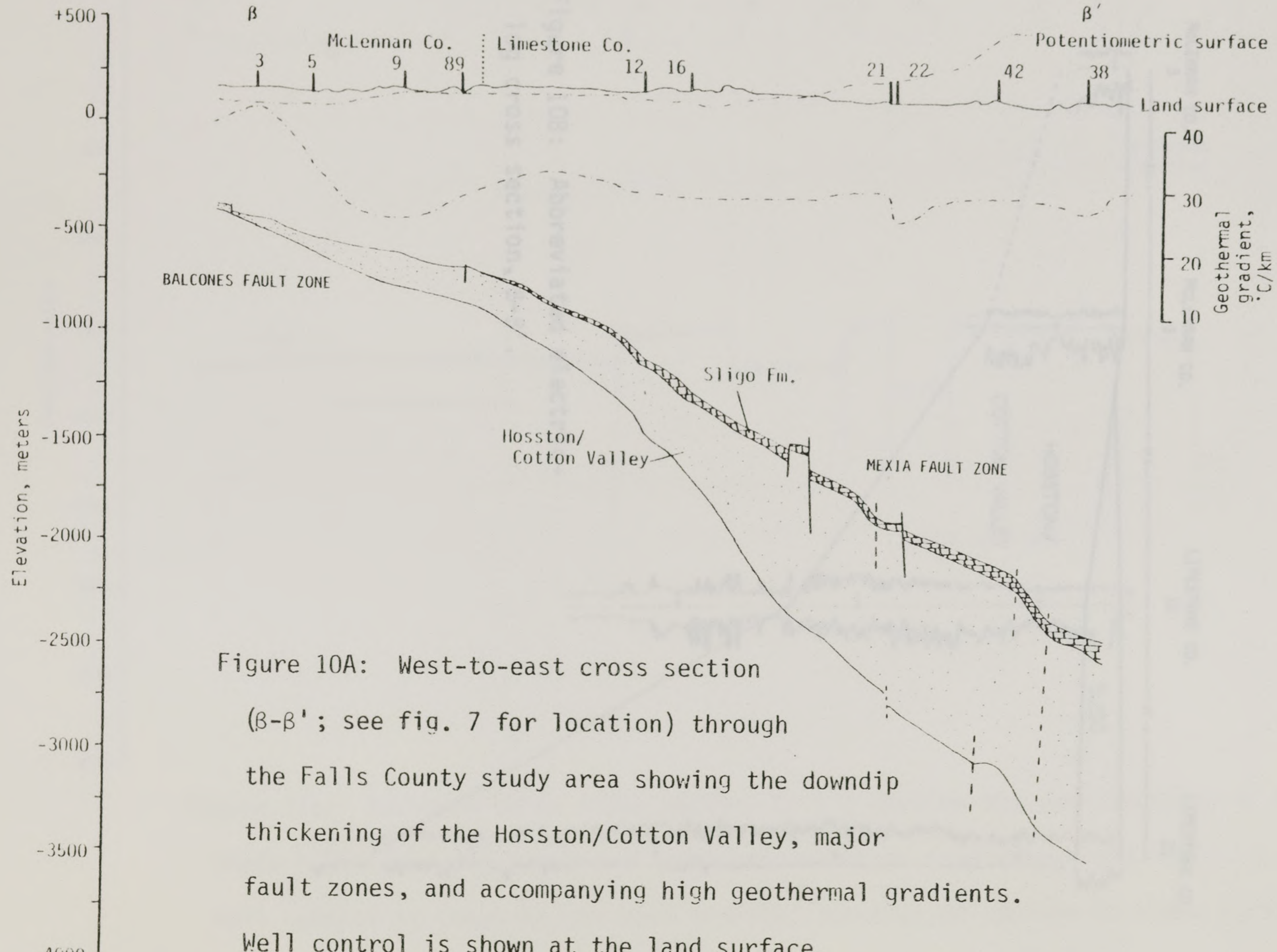


Figure 10A: West-to-east cross section (β-β'; see fig. 7 for location) through the Falls County study area showing the downdip thickening of the Hosston/Cotton Valley, major fault zones, and accompanying high geothermal gradients. Well control is shown at the land surface.

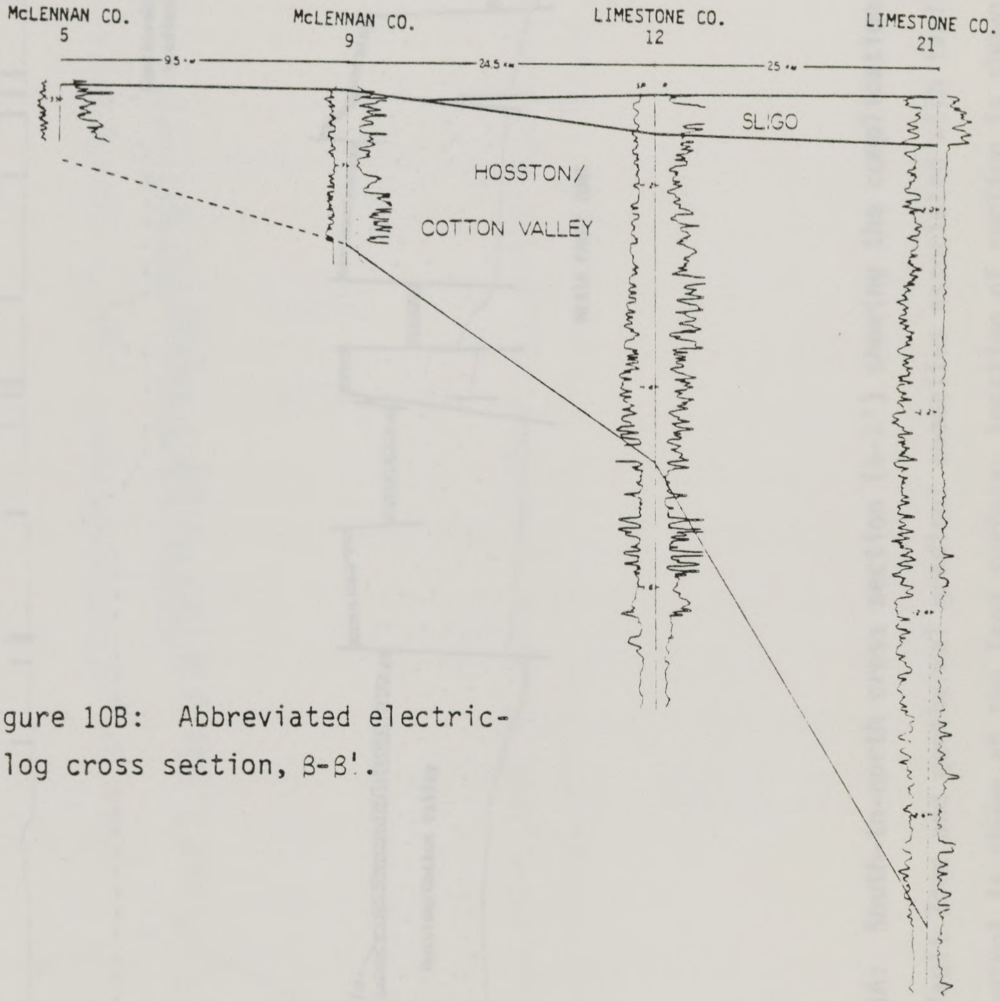


Figure 10B: Abbreviated electric-log cross section, β-β'.

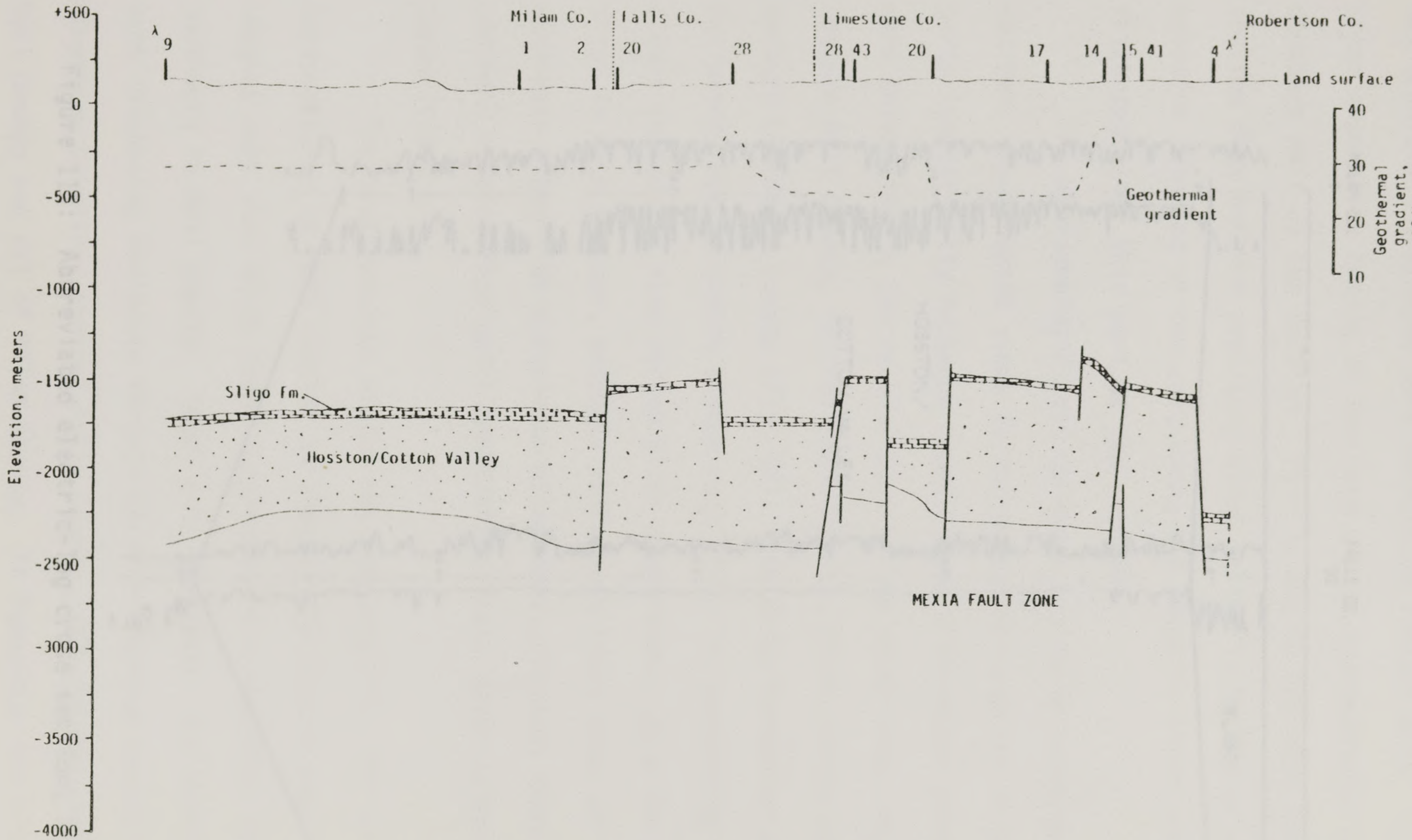


Figure 11A: South-to-north cross section (λ-λ') showing the complications of the Mexia Fault Zone and geothermal gradient anomalies associated with fault blocks. Well control is shown at the land surface; location of section is shown on Figure 7.

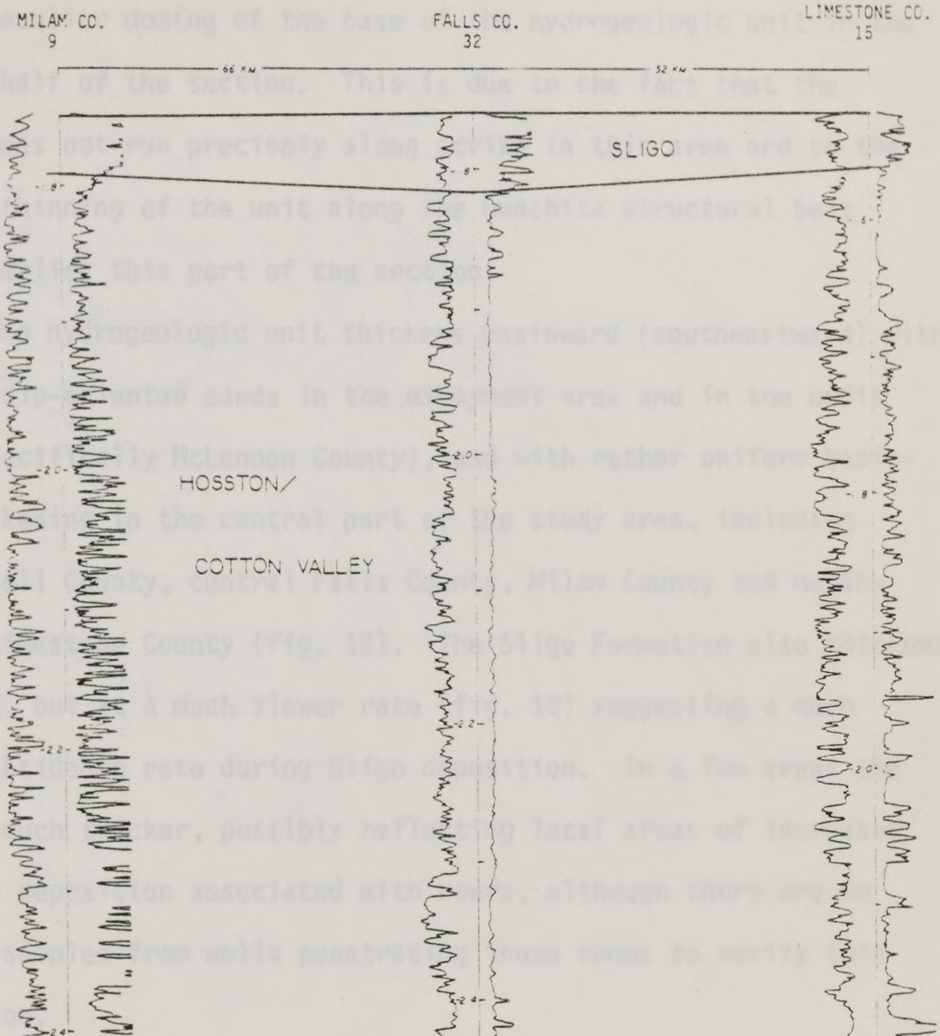


Figure 11B: Abbreviated electric-log cross section, λ-λ'.

not accurately portrayed here because of limited data. The section shows a peculiar doming of the base of the hydrogeologic unit in the southern half of the section. This is due to the fact that the section does not run precisely along strike in this area and to the relative thinning of the unit along the Ouachita structural belt which underlies this part of the section.

The hydrogeologic unit thickens basinward (southeastward) with thicker, dip-oriented sands in the embayment area and in the updip parts (specifically McLennan County), and with rather uniform basinward thickening in the central part of the study area, including eastern Bell County, central Falls County, Milam County and northwestern Limestone County (fig. 12). The Sligo Formation also thickens basinward, but at a much slower rate (fig. 13) suggesting a much slower subsidence rate during Sligo deposition. In a few areas the Sligo is much thicker, possibly reflecting local areas of increased carbonate deposition associated with reefs, although there are no sediment samples from wells penetrating these zones to verify this supposition.

The configuration of the net sand map (fig. 14) of the Hosston/Cotton Valley is very similar to that of the isopach map. The contours suggest sand axes which trend southeastward in McLennan County and southward in Bell County. These axes disappear, and uniform basinward thickening dominates through eastern McLennan and northwestern Limestone Counties, central Falls County, and through southeastern Bell County and all of Milam County. In Robertson and Limestone

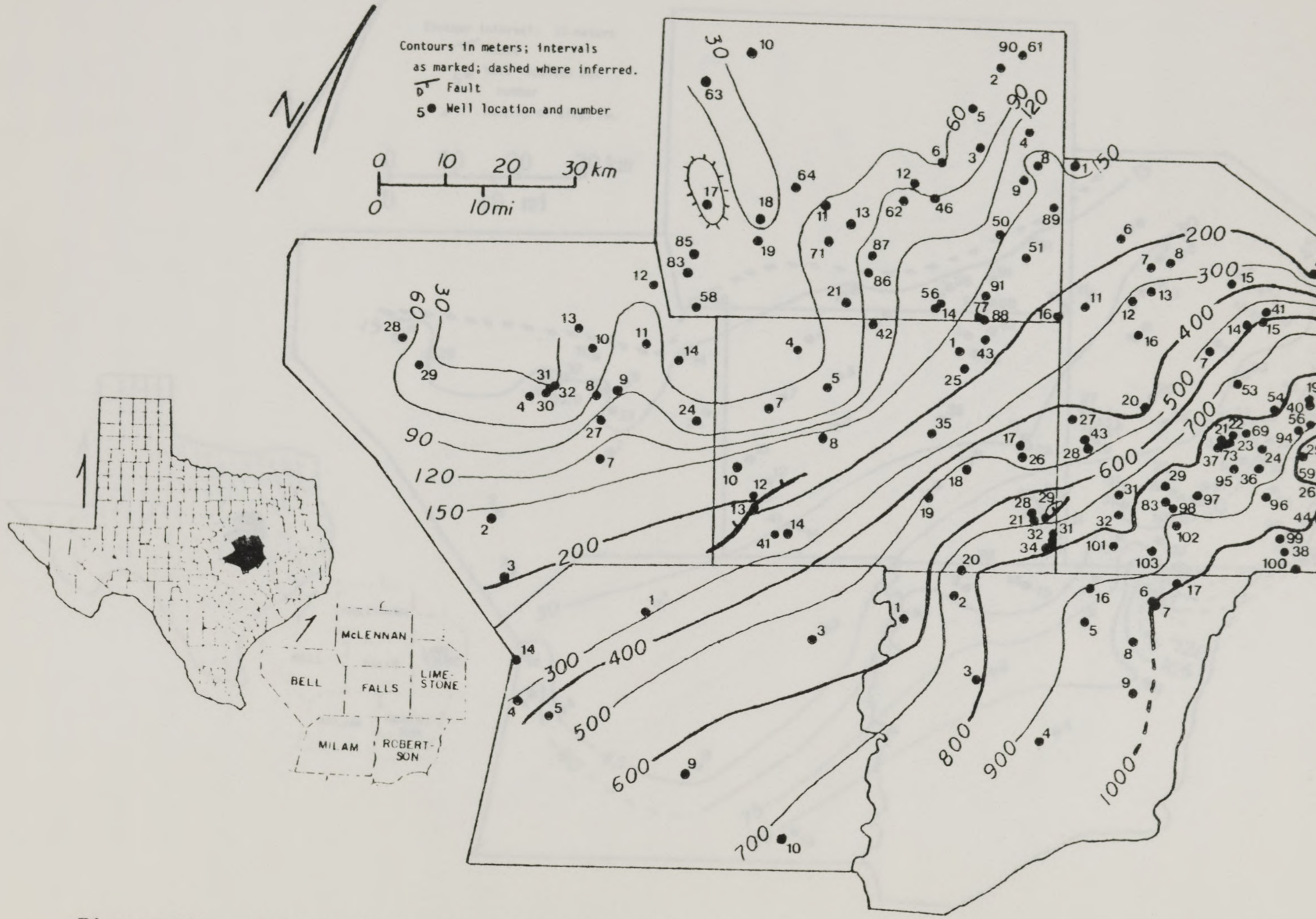


Figure 12: Isopach of Hosston/Cotton Valley hydrogeologic unit. The contour interval is larger in the eastern half of the area, reflecting basinward thickening.

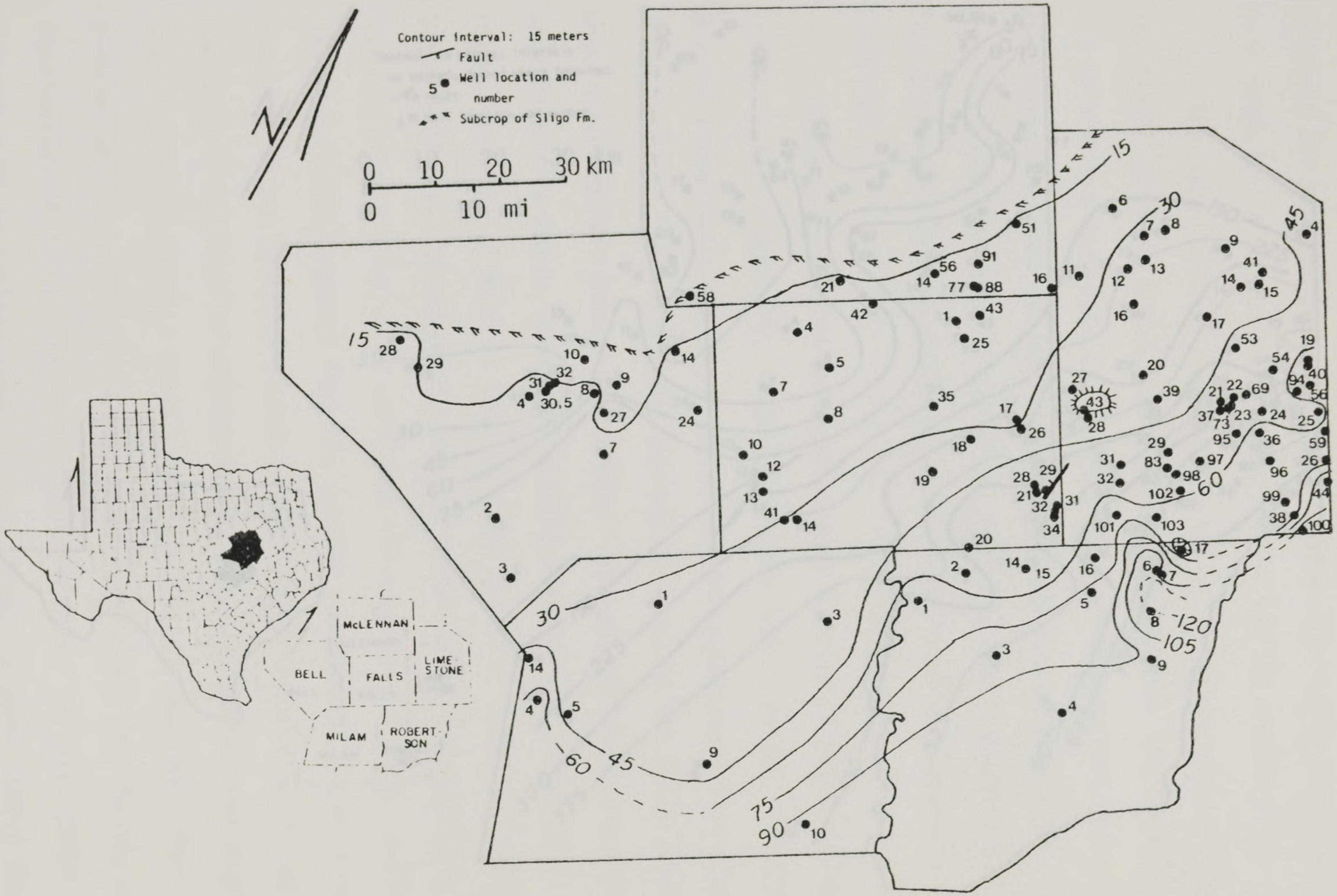


Figure 13: Isopach of Sligo Formation.

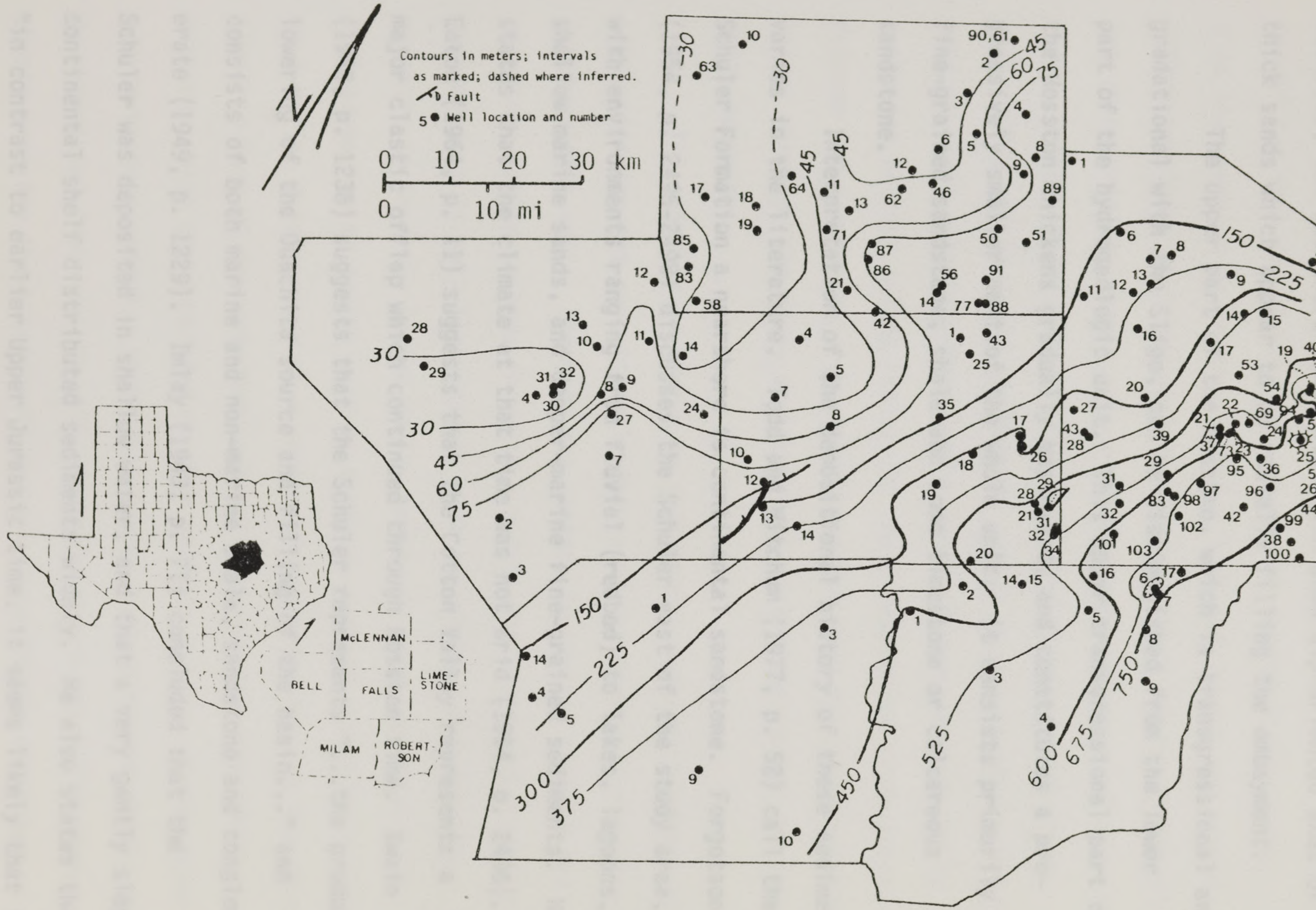


Figure 14: Net sand thickness, Hosston/Cotton Valley hydrogeologic unit. The contour interval is larger in the eastern half of the area, reflecting basinward thickening.

Counties, the basinward sediments again show dip-oriented axes of thick sands which appear to be radially filling the embayment.

The upper part of the Hosston, which is transgressional and gradational with the Sligo, can be distinguished from the lower part of the hydrogeologic unit. This upper transgressional part of the Hosston thickens gradually basinward, and constitutes a progressively smaller part of the whole unit. It consists primarily of fine-grained sandstone, shale and some limestone or calcareous sandstone.

Interpretation of the depositional history of these sediments varies in the literature. Todd and Mitchum (1977, p. 52) call the Schuler Formation a nearshore to continental sandstone. Forgotson (1954, p. 2495-2498) discusses the Schuler east of the study area, with environments ranging from fluvial (redbed) to lakes, lagoons, shallow marine sands, and deeper-marine fine-grained sediments. He states that the climate at that time was not arid (1954, p. 2498). Eaton (1964, p. 11) suggests that the Cotton Valley represents a major clastic offlap which continued through Hosston time. Swain (1949, p. 1238) suggests that the Schuler represents "...the gradual lowering of the Ouachita source and filling of the basin..." and consists of both marine and non-marine shale, sandstone and conglomerate (1949, p. 1229). Imlay (1943, p. 71) concluded that the Schuler was deposited in shallow water, and that a very gently sloping continental shelf distributed sediments widely. He also states that, "in contrast to earlier Upper Jurassic time, it seems likely that the

Cotton Valley was fed by many rivers draining the bordering highlands" and that the climate was more moist during Cotton Valley time than earlier or later. Bebout (1977) and Bebout and others (1981) concluded that the Hosston-Sligo in South Texas was deposited on an arid sea margin with sediments representative of alluvial plain, sabkha, tidal flat, lagoon and shelf margin environments. Hall (1975) and Woodruff and McBride (1978) have suggested a fluvial-deltaic model with high-destructive delta systems accompanied by extensive barrier island facies for their respective study areas. McGowen and Harris (in preparation) suggest that the Hosston/Cotton Valley north of the study area consists of braided-stream and fan-delta deposits.

The evidence presented in this report suggests a number of possibilities for the depositional history of the Hosston/Cotton Valley hydrogeologic unit. These do not conform to typical fluvial and nearshore marine systems in which a relatively large proportion of the sediment is very fine-grained silt and shale. One possible scenario is that the Cotton Valley sediments were deposited in a bedload-dominated system such as a coarse-grained meanderbelt system, or a marine system, such as a series of submarine fans or fan deltas. Electric logs of the presumed Cotton Valley section show three patterns which are separated by thin shales: blocky, fining upward and coarsening upward. Individual sands, 3 to 30 meters thick, cannot be correlated from well to well and there are no extensive shales. The source area for these sediments may have been fairly close by, as suggested by chert conglomerates, although the sands are generally well sorted and sub-angular to rounded. These descriptions also apply to the lower part of the Hosston sediments, because these were not differentiated in this report. There may or may not have been a time of non-deposition between the Hosston and Cotton Valley. Hosston sediments in the northwestern half of the study area reflect both dip-oriented and strike-oriented systems. The updip Hosston is generally a coarse-grained fluvial deposit whereas the downdip Hosston is presumably similar to the Cotton Valley in depositional history since the sediments are similar. The strike-oriented system between the updip and downdip dip-oriented systems may represent deposition of sand sheets on a shallow continental shelf, through which it was transported to submarine fans which filled the local embayment.

GROUND-WATER HYDROLOGY

Hydrologic Properties

General

Aquifer yield can affect the feasibility of low-temperature geothermal ground water as a resource. An aquifer which produces a small volume of water is less valuable than one from which heat can be extracted from a large volume of water. The ability to produce water is quantified by measuring the hydrologic properties of the aquifer. These properties--hydraulic conductivity, transmissivity and storativity or storage coefficient--describe the rate at which water can be produced from an aquifer, and, to a certain extent, the amount of water available for use. Hydraulic conductivity, K, is the quantity of water that will flow through an aquifer cross section of one square unit, under a hydraulic gradient of one, over a unit period of time. Transmissivity, T, is the volume of water that will flow through a one-unit wide strip which extends through the entire (saturated) thickness of the aquifer, under a hydraulic gradient of one, over a unit period of time (Johnson Division, 1972, p. 102). Therefore, transmissivity is related to hydraulic conductivity by:

$$T = K \times b$$

where T = transmissivity

K = hydraulic conductivity

b = the saturated thickness of the aquifer

Storage coefficient, S, is the volume of water released from storage per unit area of the aquifer per unit decline in head (Freeze and Cherry, 1979, p. 60). It is a dimensionless term that has values with magnitudes ranging from 10^{-1} to 10^{-2} for unconfined (water-table) aquifers where it is more properly termed specific yield, to magnitudes of 10^{-3} to 10^{-5} and less for confined (artesian) systems. Therefore, for a given change in head, much more water can be removed from storage in an unconfined system than in a confined system.

Values for each of these parameters can be determined in the field by conducting pumping tests of wells. The test to determine storage coefficient requires close proximity of at least one observation well to the pumping well, an arrangement which is uncommon. Transmissivity can be determined from a pumping test of a single well (single-point drawdown) although use of an observation well can improve data reliability. Hydraulic conductivity is calculated from transmissivity using the relationship stated above, where b may be the length of the actual production interval of the well or the permeable, saturated thickness of the aquifer penetrated by the well, regardless of actual screen length.

Although pumping tests are the most valuable source of information about the hydrologic properties of an aquifer, the tests are fraught with uncertainties about the exact conditions in the well and in the aquifer which is being measured. Some of the physical conditions of the well which affect test results are position within the aquifer, length (of screened zone) and type of completion of the production interval; degree of well development; and age of the well(s) being tested. Some limitations of the test itself, excluding assumptions and limitations in the mathematical calculations, include the accuracy of the measuring apparatus; the length of the test; boundary effects such as facies changes, structural features and leakage; as well as the purpose for which the test is designed.

Besides the limitations listed above, pumping tests are rarely run because of the time and cost incurred. Instead of a pumping test, a performance test is usually run soon after the well is drilled and before it is put into service. A performance test measures only well yield, that is, specific capacity (flow rate per unit drawdown), and does not directly measure the transmissivity of the aquifer. The primary reason for such a test is pump sizing. Commercial, industrial, or city public-supply wells are usually tested with more care than are individually-owned wells because of the larger demand placed on the larger wells. These wells are located near or within population centers, and so the best data are clustered around and in population centers. Rural water supply corporation wells are other good sources of data, and are especially valuable because of their locations away from population centers.

Previous Investigations

Regional trends in aquifer properties, although extremely valuable, are rarely delineated because of paucity and poor quality of data. Table I summarizes the results of pertinent hydrologic studies which include the study area of this report. Until very recently, investigators reported only ranges and averages of hydrologic properties based on results of the relatively few pumping tests in the area. The method used by Macpherson and Woodruff (1981) and Woodruff and others (1981) to deduce regional trends in hydrologic properties is explained below since it is used in this report.

Method

Three types of data constitute the hydrologic-properties data base, from which regional trends were deduced. The most valuable of these is pumping tests for which raw test data and supporting information allowed direct computation of hydrologic properties. These are available from the Texas Department of Water Resources (TDWR) files. Some transmissivities and hydraulic conductivities were compiled from the literature (Meyers, 1969, primarily). These are less reliable because the conditions under which the tests were run are not supplied. Finally, nearly half of the data are transmissivities estimated from performance tests in which the testers

Table I: Summary of literature discussing hydrologic properties of the Hosston Sand, Falls County area, Texas.

AUTHOR	LOCATION	T^1	K^2	S^3	COMMENTS
Klemt and others, 1975	Central Texas (including Bell, Falls, and McLennan Cos.)	560	0.7-7	2.8-7.7	K low in Balcones fault zone, very low in western part of study area. T is predicted maximum.
Cronin and others, 1973		112		5	Discusses well yields; T is average of 7 wells in the region; S is average of 3.
Sundstrom and others, 1948					Discusses well yields.
Sundstrom and others, 1949					Discusses well yields.
Guyton and Rose, 1945	Bell, Coryell, and other counties	107 113		4.8	7 wells in Bell Co., 12 in Coryell Co. T values are averages for two computation methods; S is average of all values.
George and Burns, 1945	Waco area, McLennan County	56-142		6.2-12	Range for 3 wells.
Macpherson and Woodruff, 1981	North-central Texas				Regional trends in T and K, and relationship to geology.
Woodruff and others, 1981	North-central Texas				

[1] Transmissivity, $m^2\ d^{-1}$

[2] Hydraulic conductivity, $m\ d^{-1}$

[3] Storage coefficient, dimensionless, $\times 10^{-5}$

determined only the specific capacity of the aquifer at the well. These also were compiled from TDWR files.

Various methods of estimating transmissivity from specific capacity values have been developed. They are derived from either the Theis equation (Theis, 1935):

$$s = C \times \frac{Q \times W(u)}{T} \qquad \text{where } u = C \times \frac{r^2 \times S}{T \times t}$$

for nonequilibrium conditions; or the Thiem equation for equilibrium conditions in confined aquifers (Thiem, 1906):

$$T = C \times \frac{Q \times \log_{10}(r_2/r_1)}{(s_1 - s_2)}$$

where T = transmissivity

S = coefficient of storage

Q = discharge rate

$W(u)$ = well function of u

$r_2, r_1, r, r_{cone}, r_{well}$ = radii

s_2, s_1, s = drawdown

t = time of pumping

C, C' = constants

Lohman (1972) briefly summarizes some of the methods; others include that developed by Ogden (1965), Walton (1962) and Thomasson and others (1960). In general, these methods manipulate one or both of the above basic ground-water flow equations and put transmissivity in terms of specific capacity, Q/s (flow rate per unit drawdown):

$$T = C \times \frac{Q}{s} \times \log_{10}\left(C' \times \frac{T \times t}{r^2 \times S}\right)$$

$$T = C \times \frac{Q}{s} \times \log_{10}\left(\frac{r_{cone}}{r_{well}} \right)$$

Comparison of these two equations shows that the second one, derived from the Thiem equation, assumes equilibrium conditions and thus does not take into account the time of pumping or the storage coefficient. The minimum test period for tests used in this report is two hours since the vast majority of performance tests were run for two to twelve hours. However, since one cannot tell from specific capacity alone whether or not equilibrium is attained, and because a confined aquifer is usually pumped for 24 hours and an unconfined aquifer for three days or more (Johnson Division, 1972, p. 115) to attain equilibrium during an aquifer test, it is not legitimate to assume equilibrium conditions for the performance tests used in this study. Besides this, neither equation shown above takes into account well efficiency or partial penetration.

The method for estimating transmissivity in this study is that developed by Theis and others (1963) because this method includes corrections for time of pumping, storage coefficient, well radius and effective well radius (as influenced by well development). As a first approximation, the wells were considered 100 per cent efficient (no loss in head due to incomplete well development, inappropriate well completion, clogging of well openings by chemical precipitates or bacteria, and the like) because of the difficulty in assessing the degree of well development or other factors affecting efficiency, and because the uncertainty in the calculation overshadowed uncertainty due to well efficiency.

The Theis method of estimating transmissivity involves calculation of T' which is a function of the specific capacity of the well, the well radius, the specific yield or storage coefficient and the time of pumping:

$$T' = \frac{Q}{s} (W - C_1 \times \log_{10}(C_2 \times S) + C_1 \times \log_{10}(t)$$

where $W = -C_3 - C_1 \times \log_{10}(C_4 \times r^2)$

C_1-C_4 = constants

I estimated storage coefficients or specific yields for the equation using values calculated from nearby pumping tests; or, if no tests were available, using values quoted in the literature as regional average estimates; or, as a last resort, assuming that for confined aquifers the storage coefficient is approximately the thickness of the aquifer times 10^{-6} m^{-1} (Lohman, 1972, p. 53). Since transmissivity varies with the logarithm of the storage coefficient, litte error is introduced when the estimate of S is wrong by even an order of magnitude.

The Theis method uses a graph to compart T' with the specific capacity; the graph (fig. 15) is based on the relationship:

$$T' = T - C \times \frac{Q}{s} \times \log_{10}(T \times 10^{-5})$$

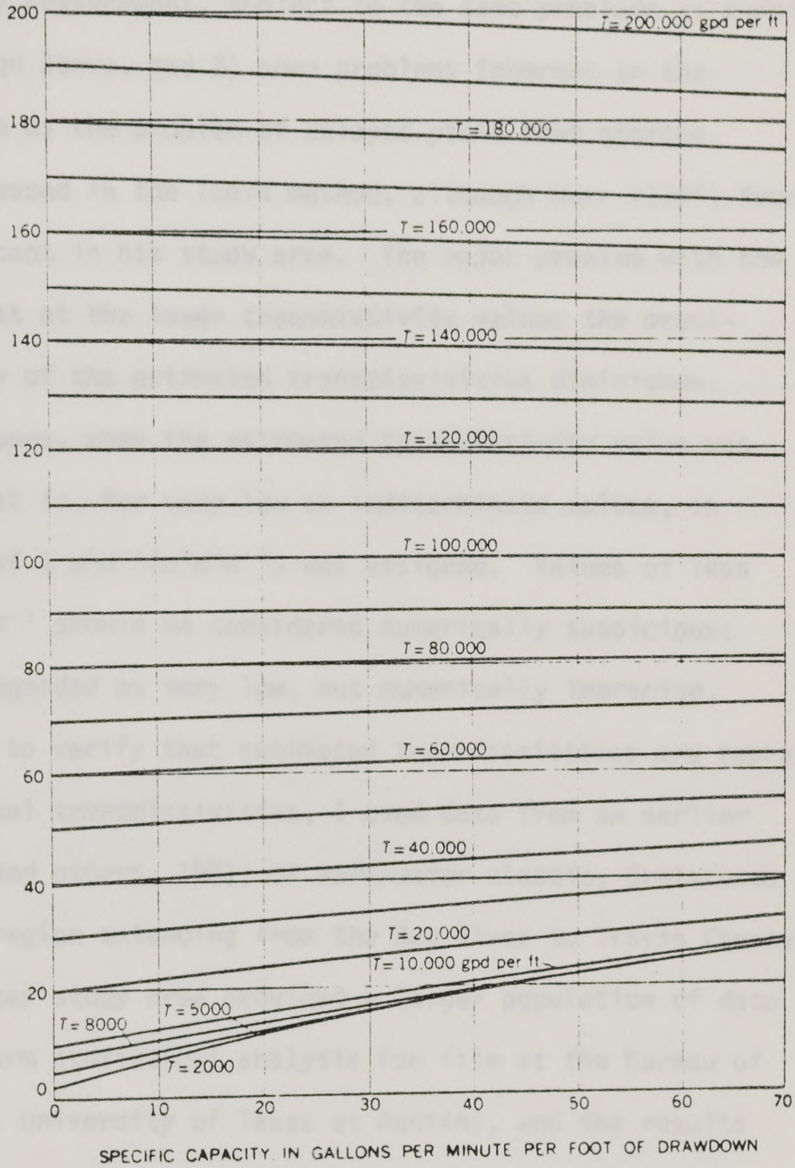


Figure 15: Graphical method of estimating transmissivity from specific capacity (Theis and others, 1963).

The limitations of this relationship include 1) the validity of the specific capacity measurement, subject to the same problems as pumping tests as described above, and 2) some problems inherent in the calculation, such as the problem of delayed yield from storage. This is not addressed in the Theis method, although Hurr (1966) found it to be significant in his study area. The major problem with the estimation is that at the lower transmissivity values the precision and accuracy of the estimated transmissivities diminishes. For mapping purposes, when the estimated transmissivity value was questionable, that is, for very low or indeterminate values, an arbitrary value of 1 $m^2d^{-1}(m^3m^{-1}d^{-1})$ was assigned. Values of less than about 10 m^2d^{-1} should be considered numerically suspicious; they should be regarded as very low, but numerically imprecise.

In order to verify that estimated transmissivities are representative of actual transmissivities, I used data from an earlier study (Woodruff and others, 1981) of warm-water clastic, Cretaceous aquifers in the region extending from the Red River to Travis County, Texas. This larger study area provided a larger population of data on which to perform statistical analysis (on file at the Bureau of Economic Geology, University of Texas at Austin), and the results of the analysis proved instrumental in designing the program for this study, as explained below.

Frequency distributions for estimated and pumping-test transmissivities in the larger, regional study area are similar; the estimated values are generally conservative. The distribution of percent error between estimated and pumping-test transmissivities which were calculated for the best-quality tests shows that most error values were ±20%, and that the best correlations correspond to the medium-range transmissivities. To compensate for the error, contour intervals on the maps in this report are numerically closely spaced in the lower transmissivity ranges and numerically farther apart with increasing transmissivity values. In comparison, Theis and others (1963) do not attempt to validate their estimated-transmissivity method; Hurr (1966) made one such comparison with an error of about 11%; Ogden (1965) found estimated values ranging from 57% to 117% of the pumping-test values.

Results and Discussion

The hydrologic properties data used to construct Figures 16 and 17 and other data mentioned in the following discussion are listed in Appendix II. The data include 30 values calculated from pumping tests, 12 reported values and 27 estimated transmissivities. Transmissivities from pumping tests were calculated using the method developed by Cooper and Jacob (1946). Almost all the tests were single-point drawdown tests; nine involved at least one observation well and storage coefficients were calculated. The tests for which transmissivities had not already been calculated and reported in the literature are included in Appendix IV.

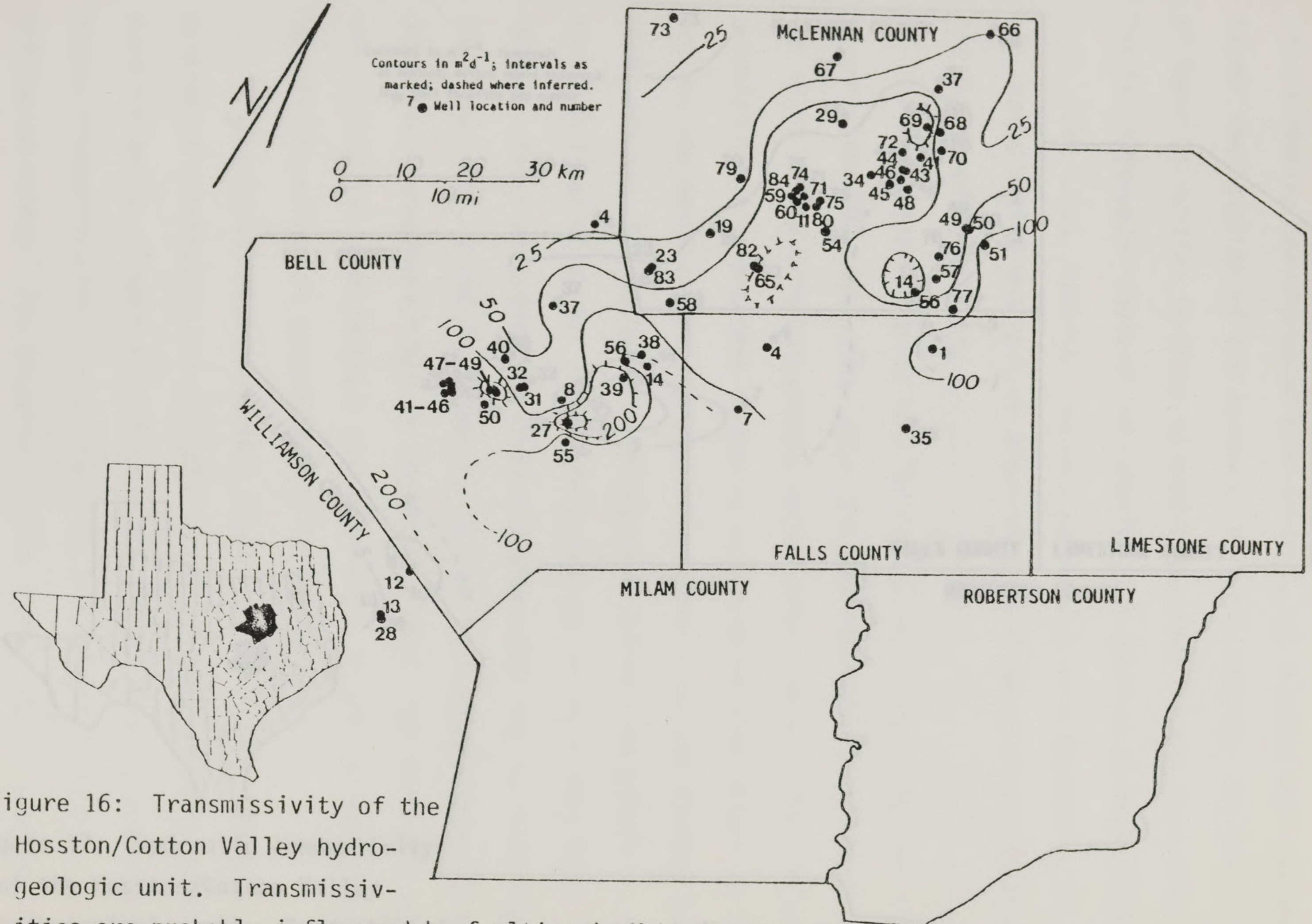


Figure 16: Transmissivity of the Hosston/Cotton Valley hydrogeologic unit. Transmissivities are probably influenced by faulting in McLennan County and depositional history in Bell County.

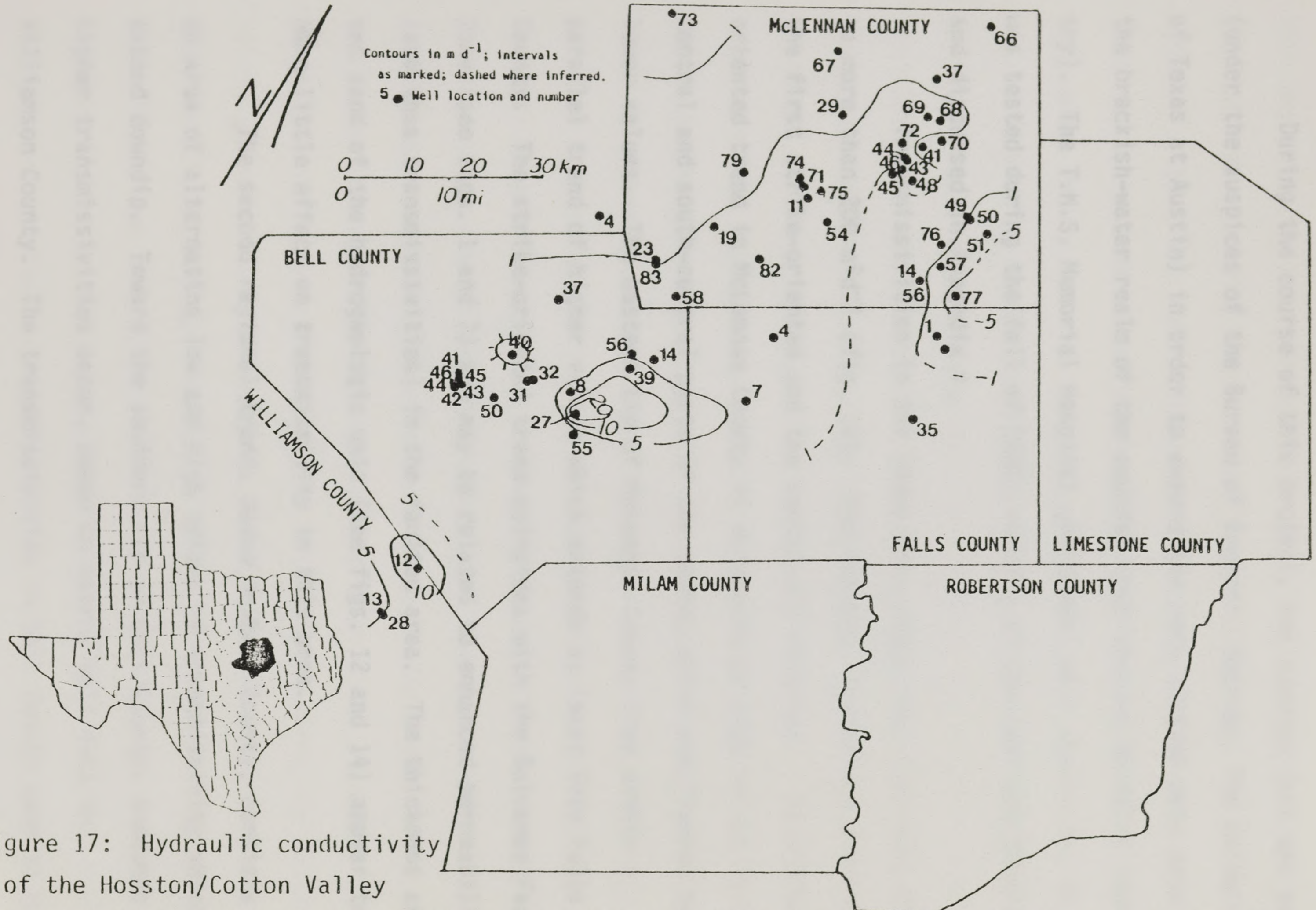


Figure 17: Hydraulic conductivity of the Hosston/Cotton Valley hydrogeologic unit. Conductivities are probably influenced by faulting in McLennan County and depositional history in Bell County.

During the course of this project, one pumping test was performed (under the auspices of the Bureau of Economic Geology, The University of Texas at Austin) in order to expand the very limited data base in the brackish-water realm of the aquifer (see section on Water Chemistry). The T.H.S. Memorial Hospital geothermal well (Falls Co. no. 35) was tested during the fall of 1980; results of the test are displayed and discussed in Appendix V.

Transmissivities in the study area range from less than 25 m^2d^{-1} to more than 200 m^2d^{-1} (fig. 16). Two regional trends are distinct, the first strike-oriented and the second dip-oriented. The strike-oriented trend in McLennan County is evidenced by high values in the central and south-central parts of the county which are flanked by lower values. The eastern tip of McLennan County lies within a parallel trend of higher values which extends at least into Falls County. The strike-oriented trend coincides with the Balcones Fault Zone (see figs. 1 and 7) and may be related to enhanced permeabilities (and thus transmissivities) in the faulted area. The thickness and net sand of the hydrogeologic unit (see figs. 12 and 14) appear to have little effect on transmissivity in this area.

The second regional trend, found in Bell County, consists of an area of alternating low and high values of transmissivity which extend downdip. Toward the southern tip of Bell County, somewhat higher transmissivities occur, based on nearby well data in Williamson County. The transmissivities in Bell County seem to be directly related to the thickness and net-sand content of the

Hosston/Cotton Valley hydrogeologic unit (figs. 12 and 14). Areas of high transmissivity coincide with thicker sediments and with areas of higher net sands, except in southern Bell County where data are sparse and coutours are based on data in adjacent Williamson County.

Hydraulic conductivities, calculated by dividing transmissivities by the length of the production interval of the well, range from less than one to more than 20 m d^{-1} ($m^3 m^{-2} d^{-1}$). Hydraulic conductivities in clean sand, for comparison, range from about 0.9 m d^{-1} to 860 m d^{-1}(Freeze and Cherry, 1979, p. 29). The conductivities in the study area exhibit patterns similar to those of the transmissivities (fig. 17). A strike-oriented belt of slightly higher hydraulic conductivities of 1 to 5 m d^{-1} coincides with the belt of slightly higher transmissivities in central and southern McLennan County and is probably related to enhanced permeabilities along the Balcones Fault Zone. In the southwestern corner of McLennan County an area of increasing hydraulic conductivity coincides with a similar increase in transmissivity. Southern Bell County has slightly higher hydraulic conductivity along the Williamson-Bell County border, as well as an area of high conductivity in the central and east-central parts. These, like the transmissivities are probably due to deposition of coarser-grained or better-sorted sediment along the depositional axis suggested by increased thickness and net-sand thickness in that area.

The regional depiction of transmissivities and hydraulic conductivities is limited by lack of information about those parameters in the saline part of the hydrogeologic unit. Judging from geologic characteristics, this downdip region probably has lower hydraulic conductivities, since grain size decreases, and somewhat higher transmissivities, since the unit thickens into the basin (see section on Sedimentation). In contrast, the potable-water area transmissivities and hydraulic conductivities result from two different geologic phenomena: depositional history of the aquifer and its effect on sediment distribution, and structural overprint which has created disruptions in the continuity of the aquifer, which, in this case, results in enhanced hydraulic conductivity along fault zones.

Few storage coefficients have been calculated for the hydrogeologic unit in the study area (Appendix II). The available data indicate that the Hosston/Cotton Valley in this area has a storage coefficient of approximately 6×10^{-5}, which is typical of a confined aquifer. Without better pumping-test data, the distribution of storage coefficients in the area cannot be determined. This parameter is useful to some extent in determining the yield of an aquifer, but is not an indication of the "safe" yield of an aquifer, which can only be determined by performing a recharge-discharge water balance for the study area. This is beyond the scope of this report, although of definite interest to those developing a geothermal ground-water resource.

Water Movement

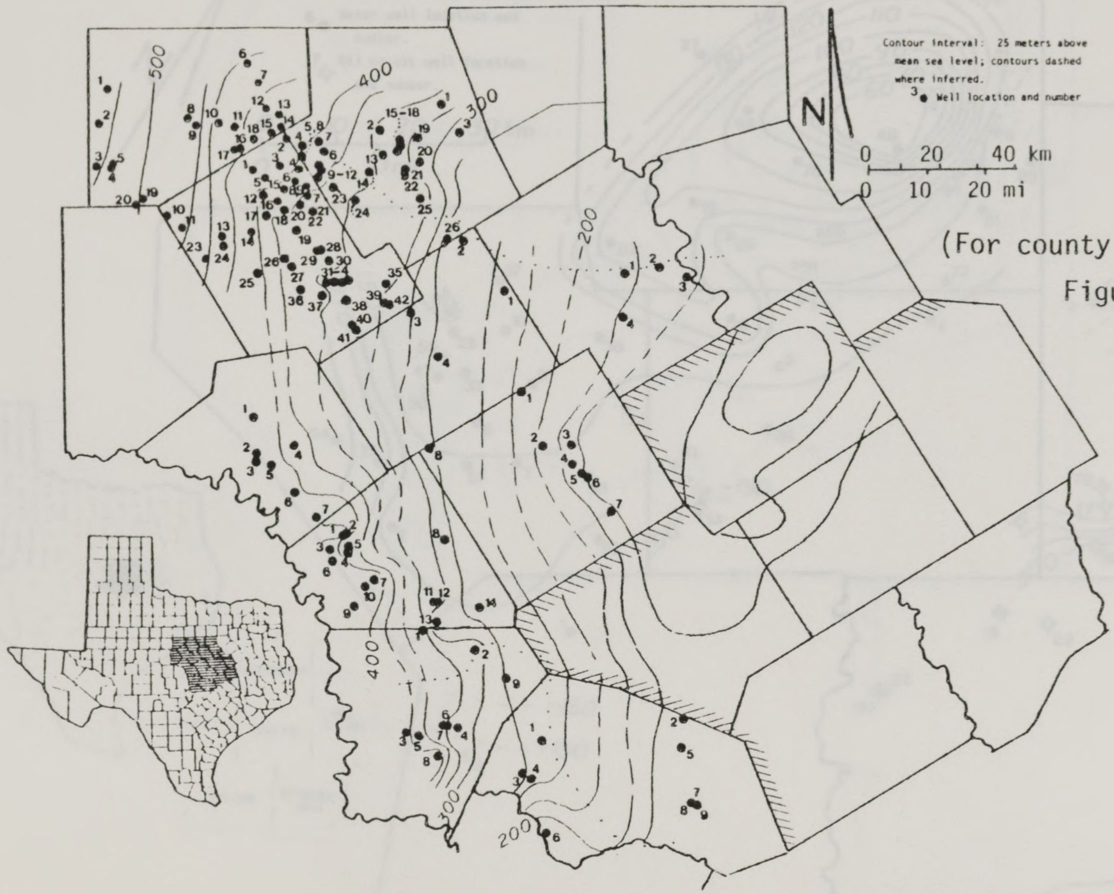
The direction and speed of movement of water through the Hosston/Cotton Valley hydrogeologic unit is critical to the distribution of usable low-temperature geothermal ground water. In general, ground water moves from areas of recharge, such as outcrops, to areas of discharge, such as springs, wells and zones where water can move up through overlying sediments. Contours of the level to which water will rise in a well indicate, in two dimensions, the direction of horizontal ground-water flow. Comparisons of potential from different depths in the same aquifer at the same well identify the vertical potential gradient or the direction of water movement in the third dimension. This is rarely measured although an important aspect of ground-water flow. There are no piezometer nests (groups of closely-spaced wells completed at different depths) in the Hosston/Cotton Valley, but in the saline water system a few wells show evidence of either positive or negative (up or down) vertical potential, based on bottom-hole pressure data.

Two different kinds of data describe water movement in the Hosston/Cotton Valley. In the western half of the study area, water levels are measured directly by means of a steel tape or electrical-sounding device. In the eastern half of the area where the Hosston/Cotton Valley is more a target for oil and gas exploration than for potable water, water levels are computed from bottom-hole-pressure measurements. In the following sections describing each of these types of data, the discussion will focus on horizontal movement since vertical movement is much harder to deduce from available data. Where data permit, vertical movement will also be discussed.

Water Level Data

Water level data for the years 1966, 1970, 1974 and 1980 were compiled from the Texas Department of Water Resources files, since data were most complete for these years (Appendix II). The data were used to construct potentiometric surface contour maps, shown in Figures 18-21. The 1966 map includes the area between the outcrop of the Lower Cretaceous sands and the study area, in order to define approximate boundaries of the hydrologic system. Ground-water divides run through Eastland, Comanche, Erath and Bosque Counties on the northeast and through Burnet, Williamson and Bell Counties on the southwest. The outcrop on the northwest and the saline water system on the southeast complete the definition of the boundaries of the fresh-water system. The saline water system in southeastern Falls, Milam, Robertson and Limestone Counties is not as well defined on the northeast and southwest sides, and presumably extends into the basin to the downdip extent of permeable sediments on the southeast.

Contours of the fresh-water hydrogeologic unit potentiometric surface during the spring of 1966 (figs. 18A and 18B) illustrate the movement of ground water from the outcrop of the Hosston Sand northwest of the study area (maximum water level elevation more than



(For county names, see Figure 5.)

Figure 18A: Potentiometric surface, Hosston/Cotton Valley hydrogeologic unit, March, 1966. Ground-water divides shown as dotted lines. Falls County study area, outlined by pattern, shown on Figure 18B.

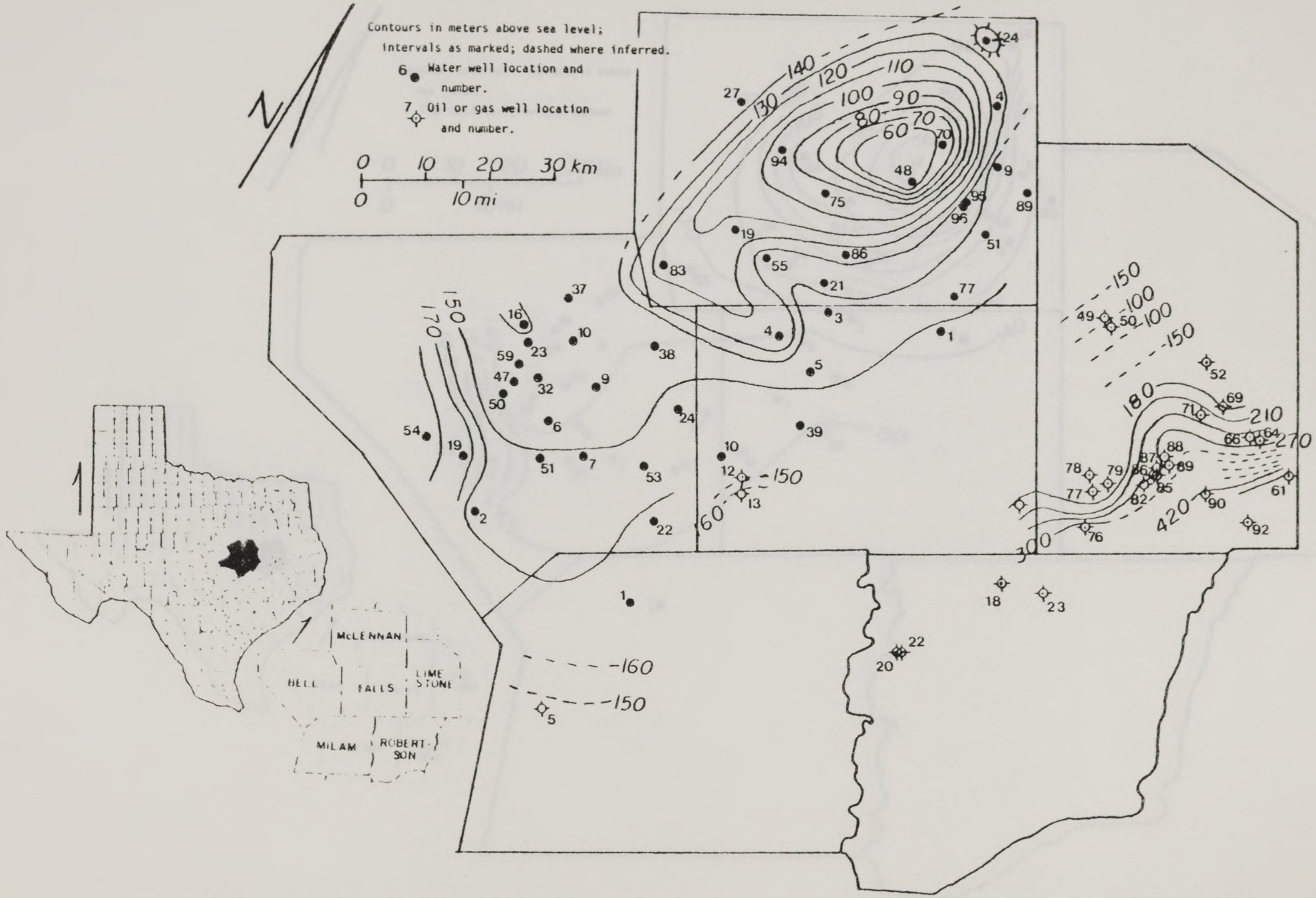


Figure 18B: March, 1966, potentiometric surface, Hosston/Cotton Valley hydrogeologic unit. In the eastern half of the study area, water-level measurements from variable dates, since basinal aquifer is probably a steady-state system.

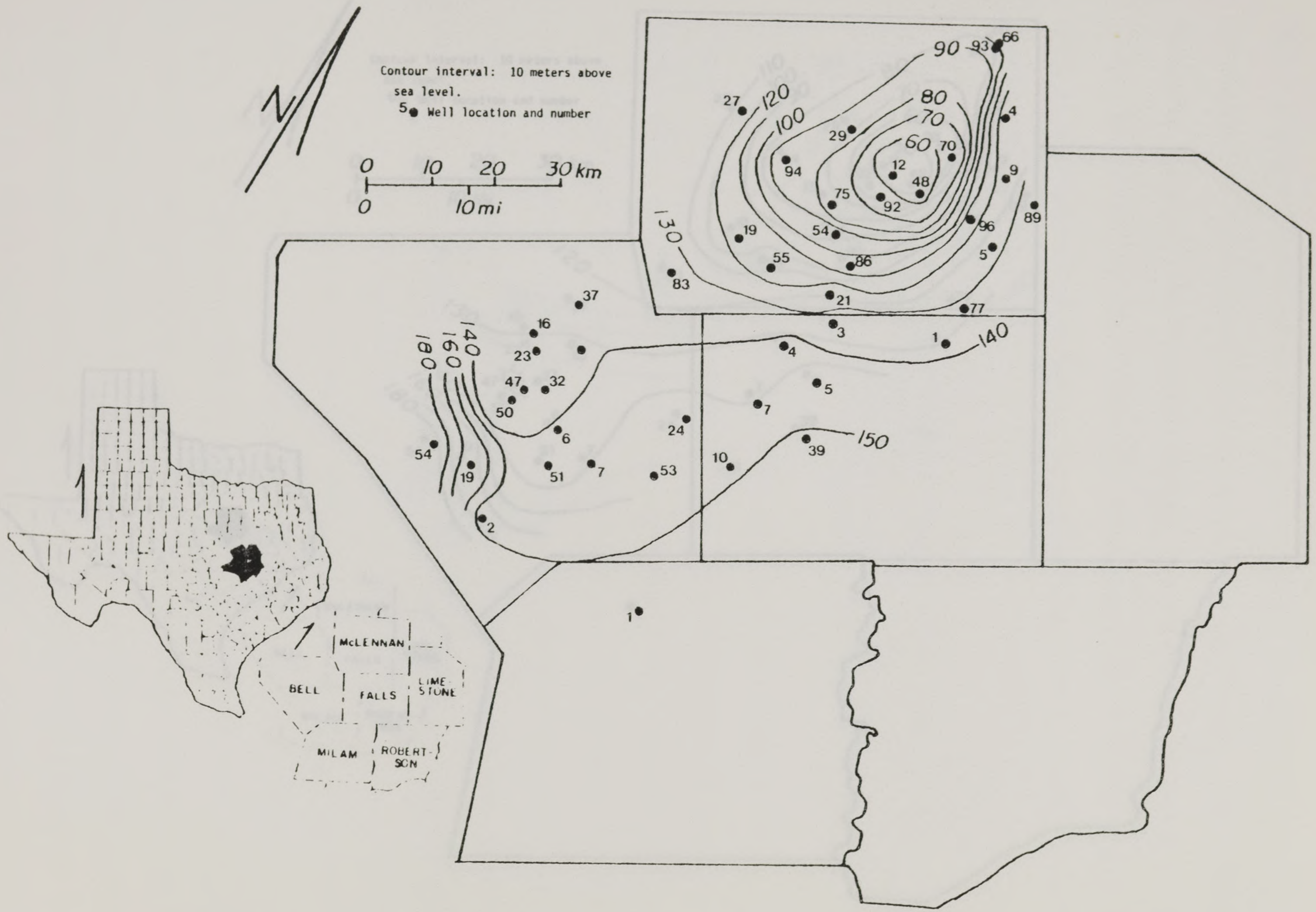


Figure 19: March, 1970, potentiometric surface, Hosston/Cotton Valley hydrogeologic unit.

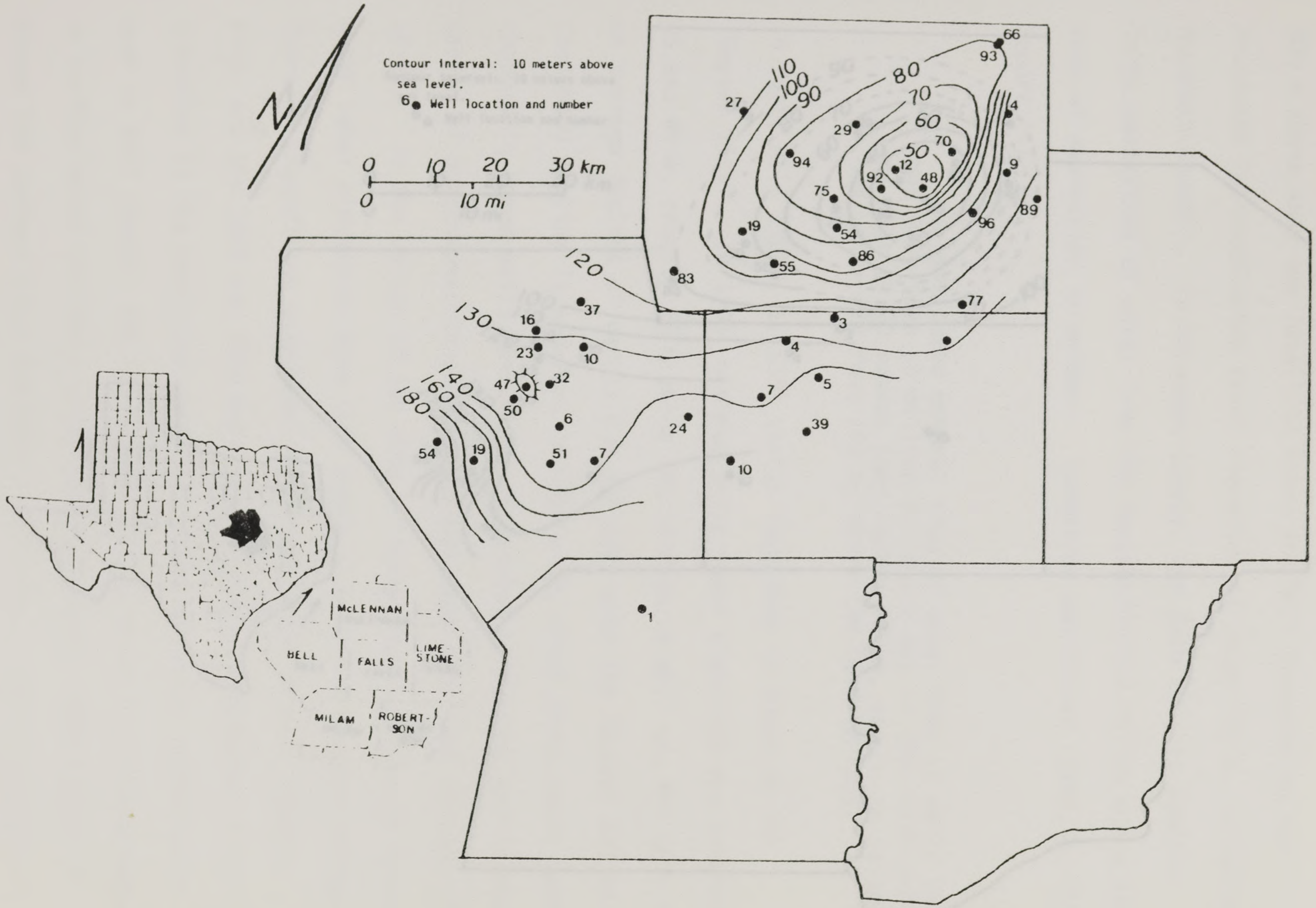


Figure 20: March, 1974, potentiometric surface, Hosston/Cotton Valley hydrogeologic unit.

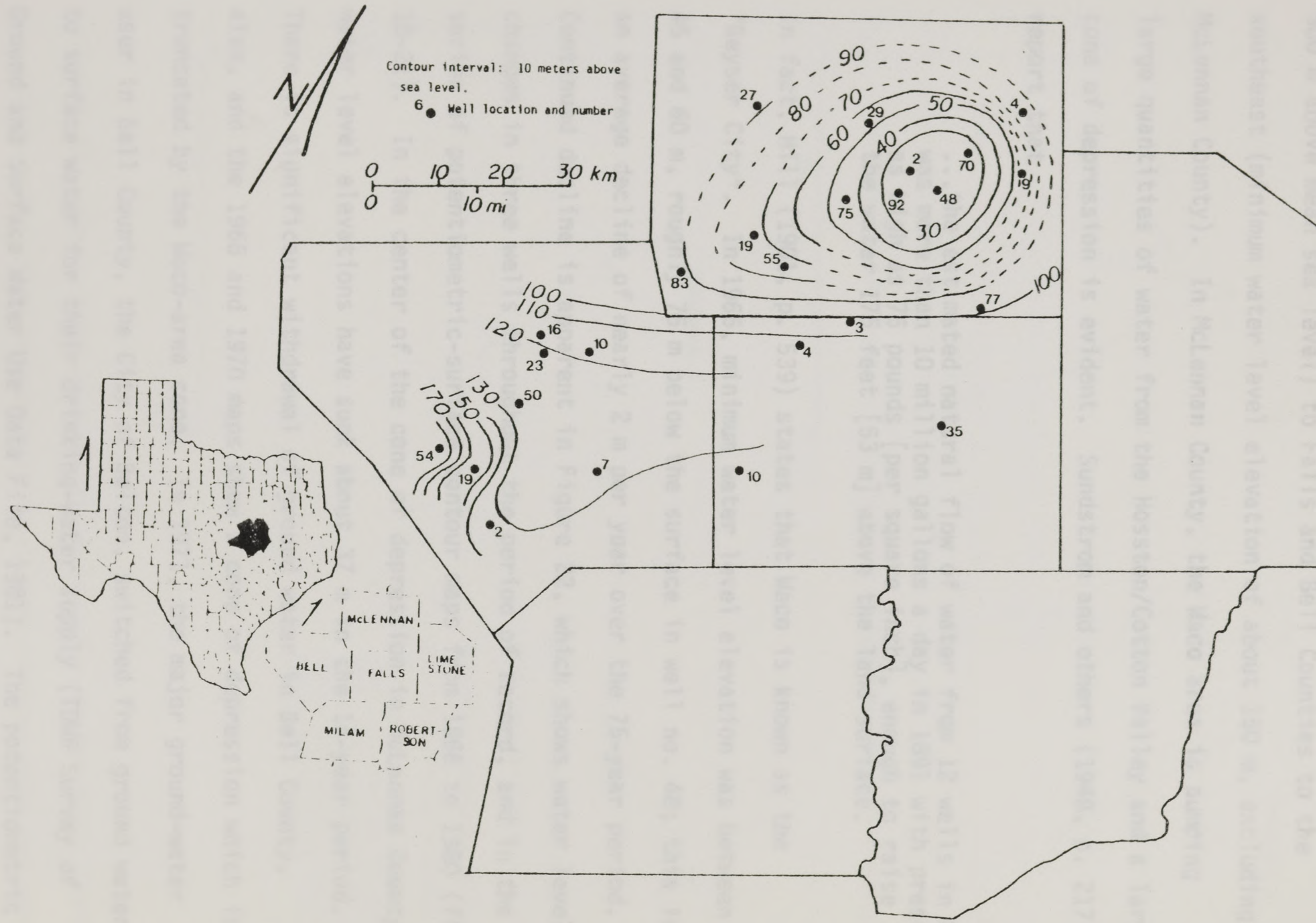


Figure 21: March, 1980, potentiometric surface, Hosston/Cotton Valley hydrogeologic unit.

500 m above mean sea level) to Falls and Bell Counties to the southeast (minimum water level elevation of about 150 m, excluding McLennan County). In McLennan County, the Waco area is pumping large quantities of water from the Hosston/Cotton Valley and a large cone of depression is evident. Sundstrom and others (1948, p. 217) report that

> ...the estimated natural flow of water from 12 wells in Waco was more than 10 million gallons a day in 1891 with pressure as high as 76 pounds [per square inch], enough to raise the water 175 feet [53 m] above the land surface.

In fact, Hill (1901, p. 539) states that Waco is known as the "Geyser City". In 1966, minimum water level elevation was between 45 and 60 m, roughly 75 m below the surface in well no. 48; this is an average decline of nearly 2 m per year over the 75-year period. Continued decline is apparent in Figure 22, which shows water level changes in three wells throughout the period of record, and in the series of potentiometric-surface contour maps from 1966 to 1980 (figs. 18-21). In the center of the cone of depression in McLennan County, water level elevations have sunk about 37 m in the 14-year period. There is significant withdrawal of ground water in Bell County, also, and the 1966 and 1970 maps show a cone of depression which is truncated by the Waco-area cone. In 1971, the major ground-water user in Bell County, the City of Belton, switched from ground water to surface water for their drinking-water supply (TDWR Survey of Ground and Surface Water Use Data File, 1981). The potentiometric surfaces in 1974 and 1980 (figs. 20 and 21) reflect this change; the

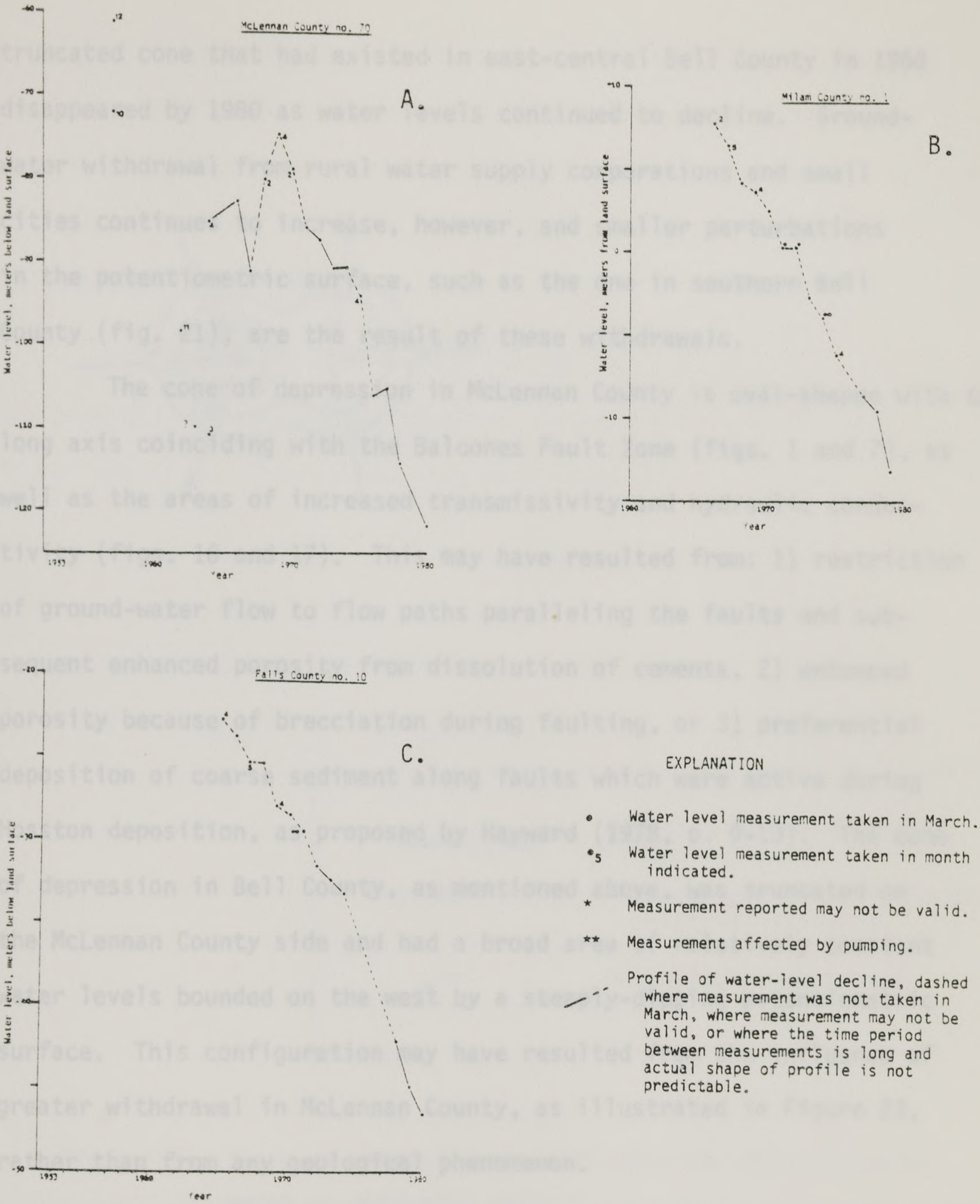


Figure 22: Water level decline in three wells in the Falls County study area. Most measurements were made between 1960 and 1980.

truncated cone that had existed in east-central Bell County in 1966 disappeared by 1980 as water levels continued to decline. Ground-water withdrawal from rural water supply corporations and small cities continues to increase, however, and smaller perturbations in the potentiometric surface, such as the one in southern Bell County (fig. 21), are the result of these withdrawals.

The cone of depression in McLennan County is oval-shaped with the long axis coinciding with the Balcones Fault Zone (figs. 1 and 7), as well as the areas of increased transmissivity and hydraulic conductivity (figs. 16 and 17). This may have resulted from: 1) restriction of ground-water flow to flow paths paralleling the faults and subsequent enhanced porosity from dissolution of cements, 2) enhanced porosity because of brecciation during faulting, or 3) preferential deposition of coarse sediment along faults which were active during Hosston deposition, as proposed by Hayward (1978, p. 9-13). The cone of depression in Bell County, as mentioned above, was truncated on the McLennan County side and had a broad area of relatively constant water levels bounded on the west by a steeply-dipping potentiometric surface. This configuration may have resulted from the influence of greater withdrawal in McLennan County, as illustrated in Figure 23, rather than from any geological phenomenon.

The relationship between ground water in the potable-water (western) part of the Hosston/Cotton Valley and in the brackish- to saline-water (eastern) part is the result of both meteoric recharge and movement of saline water. The potentiometric surface in the eastern

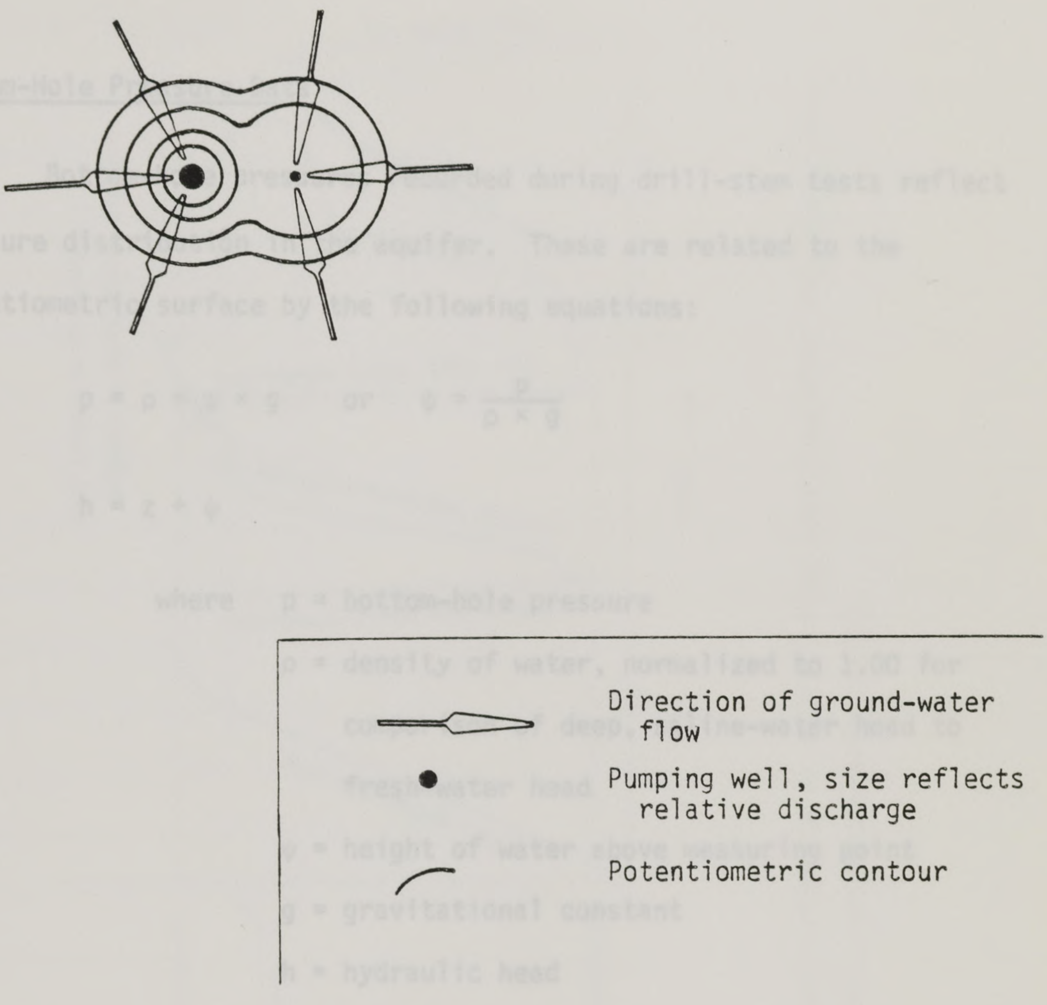


Figure 23: Shape of cone of depression when two wells withdraw water at different rates.

part of the study area is difficult to define; drill-stem tests run in oil or gas exploration wells in the downdip, saline part of the aquifer provide some clues.

Bottom-Hole Pressure Data

Bottom-hole pressures recorded during drill-stem tests reflect pressure distribution in the aquifer. These are related to the potentiometric surface by the following equations:

$$p = \rho \times \psi \times g \quad \text{or} \quad \psi = \frac{p}{\rho \times g}$$

$$h = z + \psi$$

where p = bottom-hole pressure

ρ = density of water, normalized to 1.00 for comparison of deep, saline-water head to fresh-water head

ψ = height of water above measuring point

g = gravitational constant

h = hydraulic head

z = elevation head

During a drill-stem test, pressures sensed in a gauge on the bottom of the tool are recorded on a graph or chart which reflects pressure build-up or recovery from the time the tool is lowered into the well until the tool is pulled out of the well. Figure 24 shows the basic components of a typical test. When test charts are available, the

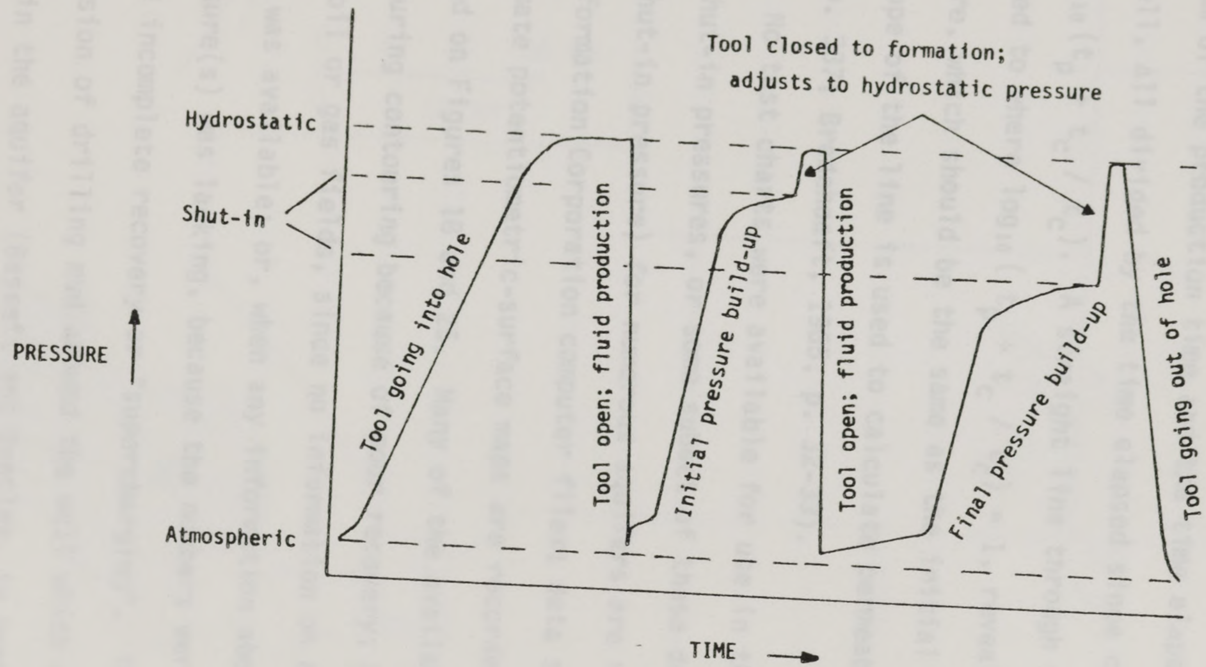


Figure 24: Basic elements of a drill stem test (modified from VanPoollen, 1961, and Bredehoeft, 1965).

data can be used to calculate permeabilities (hydraulic conductivities) and to verify that initial shut-in pressures represent aquifer pressures. The build-up pressures are plotted against the logarithm of the sum of the production time and the time elapsed since closing in the well, all divided by the time elapsed since closing in the well, or $\log_{10}(t_p + t_c / t_c)$. A straight line through the plotted points, extended to where $\log_{10}(t_p + t_c / t_c) = 1$, reveals the aquifer pressure, which should be the same as the initial shut-in pressure. The slope of the line is used to calculate permeability (VanPoollen, 1961, p. 337; Bredehoeft, 1965, p. 32-33).

No test charts were available for use in this study. Initial and final shut-in pressures, or some subset of these data (usually only the final shut-in pressure) for numerous aquifers are reported in Petroleum Information Corporation computer files; data selected to construct approximate potentiometric-surface maps are recorded in Appendix II and displayed on Figures 18 and 25. Many of the available data were excluded during contouring because of poor recovery; because of location in oil or gas fields, since no information on original reservoir pressure was available; or, when any information about the test except the pressure(s) was lacking, because the numbers were unreasonable and suggested incomplete recovery or "supercharging". The latter results from invasion of drilling mud around the well which causes increased pressure in the aquifer (Bassett and Bentley, in preparation). VanPoollen (1961, p. 338) suggests some guidelines for adequate time for pressure build-up, but these are based on length of time the well was

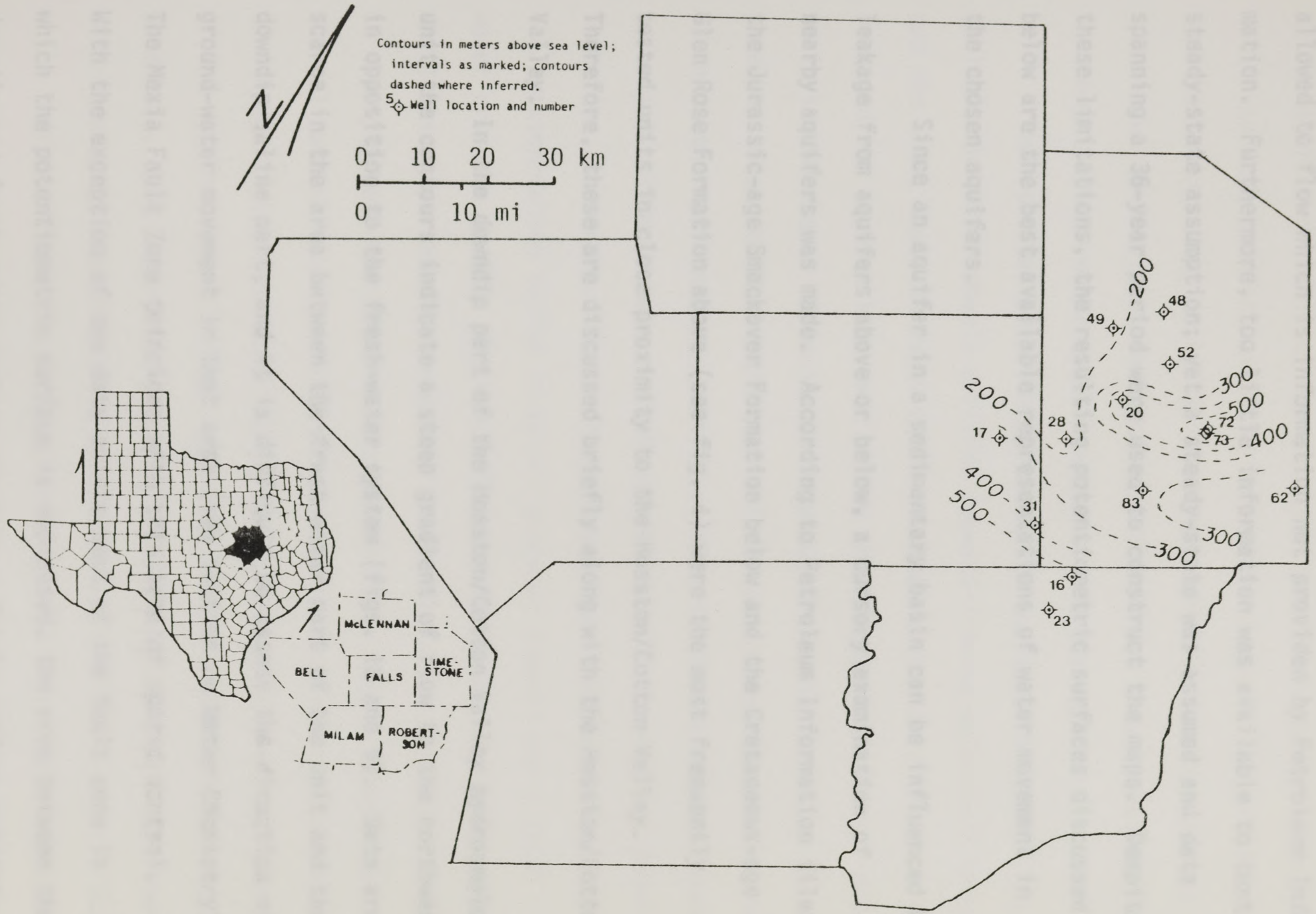


Figure 25: Possible configuration of potentiometric surface, Smackover Formation. Data are from various dates.

allowed to flow which is information not provided by Petroleum Information. Furthermore, too little information was available to test a steady-state assumption; yet a steady-state was assumed and data spanning a 36-year period were used to construct the maps. Despite these limitations, the resulting potentiometric surfaces discussed below are the best available representations of water movement in the chosen aquifers.

Since an aquifer in a sedimentary basin can be influenced by leakage from aquifers above or below, a cursory examination of nearby aquifers was made. According to Petroleum Information files, the Jurassic-age Smackover Formation below and the Cretaceous-age Glen Rose Formation above (see fig. 4) were the most frequently tested units in close proximity to the Hosston/Cotton Valley. Therefore, these are discussed briefly along with the Hosston/Cotton Valley.

In the downdip part of the Hosston/Cotton Valley hydrogeologic unit the contours indicate a steep gradient of flow to the northwest, in opposition to the fresh-water system (figs. 18 and 9). Data are scarce in the area between the fresh-water part of the unit and the downdip saline part, and it is difficult to assess the direction of ground-water movement in that area (see section on Water Chemistry). The Mexia Fault Zone coincides with this area of sparse control. With the exception of two data points west of the fault zone in which the potentiometric surface is depressed, the area between the downdip and fresh-water systems may have a fairly uniform potentiometric-surface elevation. The juxtaposition of the steep potentiometric-surface gradient with the fault zone suggests that fluids may be discharging along those faults. Certainly the data are sparse and of unknown quality, but the configuration of the potentiometric surface is thought to represent actual conditions in the aquifer.

The vertical potential gradient in the downdip part of the hydrogeologic unit is probably positive (upward-flowing potential) throughout the area, based on eight wells in which bottom-hole pressures were recorded for several intervals within the hydrogeologic unit. Potentials in the deeper Jurassic-age Smackover Formation, a major gas-producer below the Hosston/Cotton Valley, are generally greater than those in the hydrogeologic unit (fig. 25), suggesting upward-flowing potential, although data are more scattered and the contours drawn with less confidence. The Cretaceous-age Glen Rose Formation above the Hosston/Cotton Valley is an oil producer downdip and a local water producer updip. The few reliable data in this formation (Appendix II) suggest that the potential in the Glen Rose is less than that of the hydrogeologic unit in the downdip parts, again suggesting overall upward-flowing potential. In the fresh-water (updip) realm of the Glen Rose, the water level elevations are higher than those of the Hosston/Cotton Valley, suggesting overall downward-flowing potential. The zone where the relative potential changes from downward-flowing to upward-flowing is elusive because of paucity of data.

Plots of pressure-head versus depth for the Hosston/Cotton Valley hydrogeologic unit and Smackover and Glen Rose Formations (figs. 26-

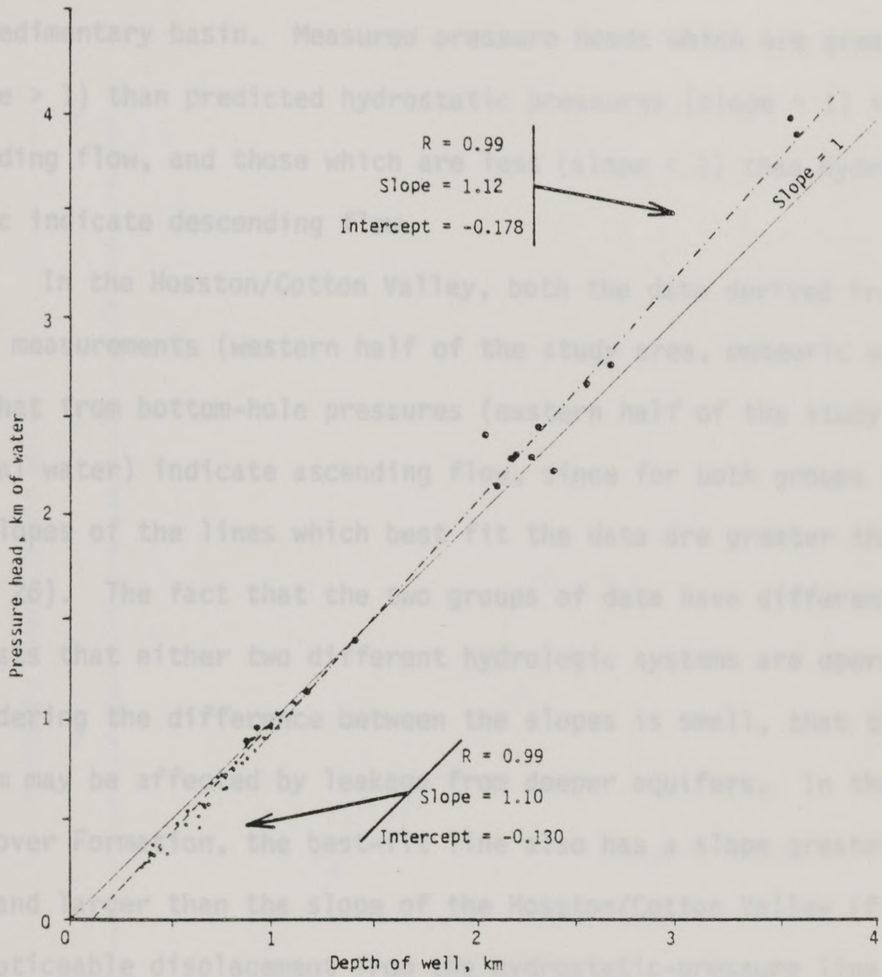


Figure 26: Relationship between pressure head and depth, Hosston/Cotton Valley hydrogeologic unit. Small dots are from water-level measurements; large dots are from bottom-hole pressures.

28) illustrate the fundamental increase in pressure head with depth. Toth (1978) used similar graphs, along with other tools, to identify gravity-induced cross-formational flow in part of the Western Canada sedimentary basin. Measured pressure heads which are greater (slope > 1) than predicted hydrostatic pressures (slope = 1) indicate ascending flow, and those which are less (slope < 1) than hydrostatic indicate descending flow.

In the Hosston/Cotton Valley, both the data derived from water-level measurements (western half of the study area, meteoric water) and that from bottom-hole pressures (eastern half of the study area, basinal water) indicate ascending flow, since for both groups of data the slopes of the lines which best fit the data are greater than one (fig. 26). The fact that the two groups of data have different slopes suggests that either two different hydrologic systems are operating or, considering the difference between the slopes is small, that the deeper system may be affected by leakage from deeper aquifers. In the Smackover Formation, the best-fit line also has a slope greater than one, and larger than the slope of the Hosston/Cotton Valley (fig. 27). The noticeable displacement from the hydrostatic-pressure line relative to that displacement in the Hosston/Cotton Valley is due to the higher head in the Smackover Formation. The Glen Rose Formation data are scattered; there was little information on record with which to select valid data from the population, so all are included on this graph (fig. 28). Despite the limited data populations for the Hosston/Cotton Valley and the Smackover, correlation coefficients are reported in order to illustrate the remarkable consistency of the data.

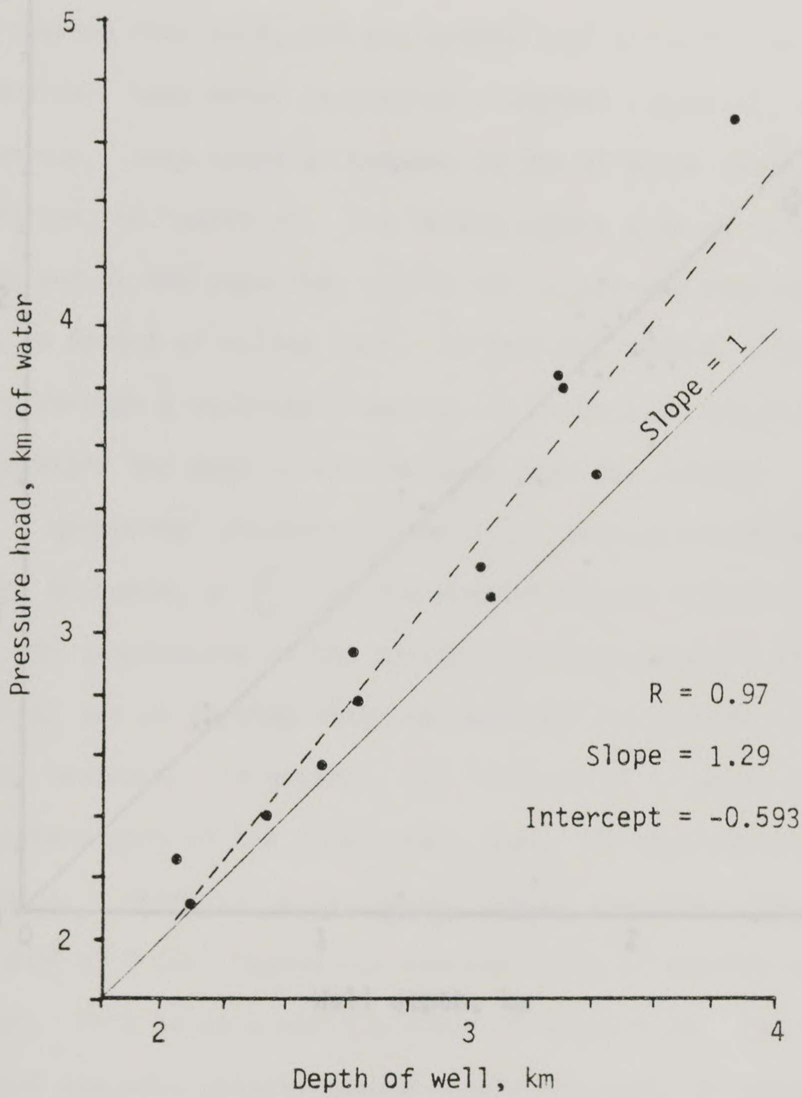


Figure 27: Relationship between pressure head and depth, Smackover Formation.

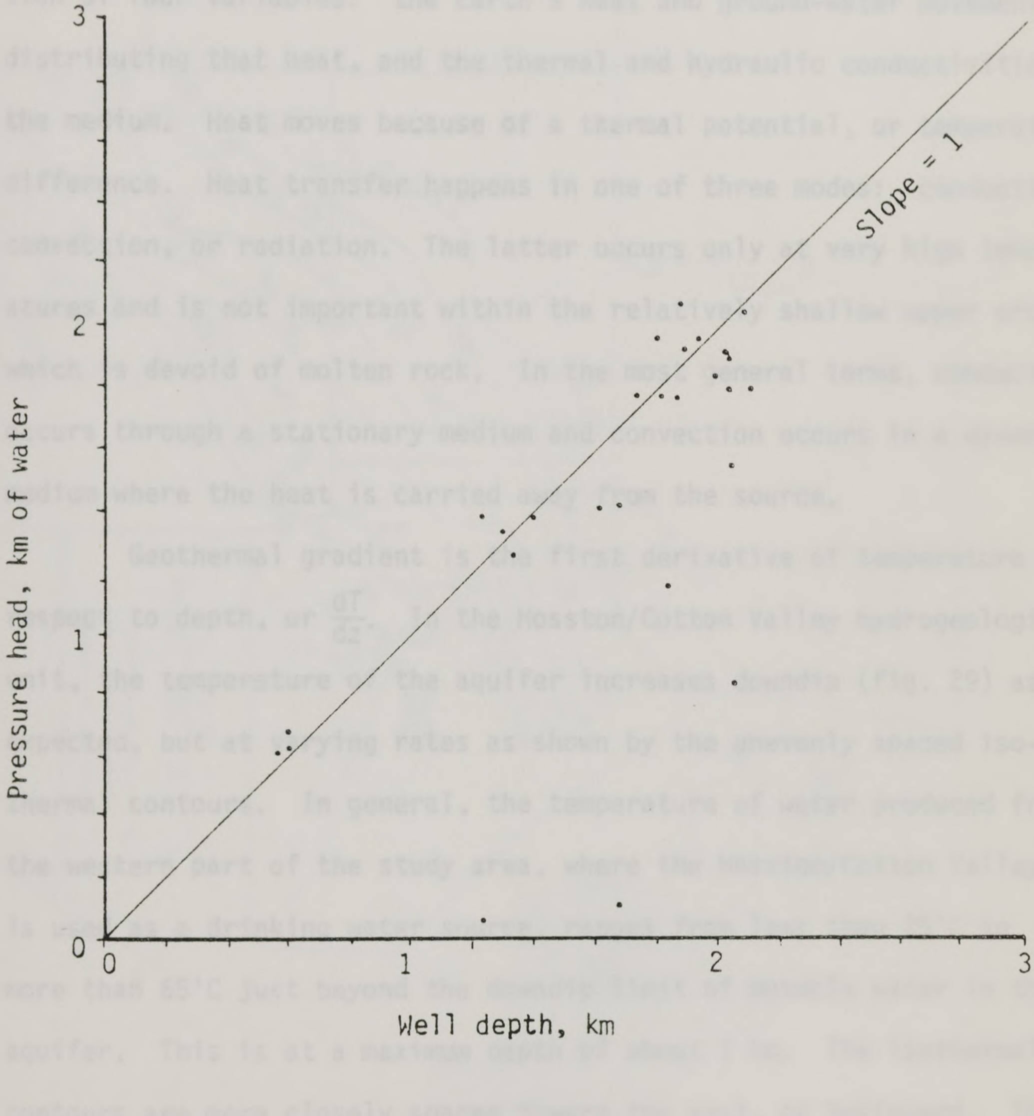


Figure 28: Relationship between pressure head and depth, Glen Rose Formation.

GEOTHERMAL REGIME

Introduction

The distribution of water temperature in an aquifer is a function of four variables: the Earth's heat and ground-water movement distributing that heat, and the thermal and hydraulic conductivities of the medium. Heat moves because of a thermal potential, or temperature difference. Heat transfer happens in one of three modes: conduction, convection, or radiation. The latter occurs only at very high temperatures and is not important within the relatively shallow upper crust which is devoid of molten rock. In the most general terms, conduction occurs through a stationary medium and convection occurs in a dynamic medium where the heat is carried away from the source.

Geothermal gradient is the first derivative of temperature with respect to depth, or $\frac{dT}{dz}$. In the Hosston/Cotton Valley hydrogeologic unit, the temperature of the aquifer increases downdip (fig. 29) as expected, but at varying rates as shown by the unevenly spaced isothermal contours. In general, the temperature of water produced from the western part of the study area, where the Hosston/Cotton Valley is used as a drinking water source, ranges from less than 25°C to more than 65°C just beyond the downdip limit of potable water in the aquifer. This is at a maximum depth of about 1 km. The isothermal contours are more closely spaced toward the east, or basinward. This is undoubtedly due to the increased rate of dip of the top and base of the aquifer (figs. 7-8) and the increasing thickness of the

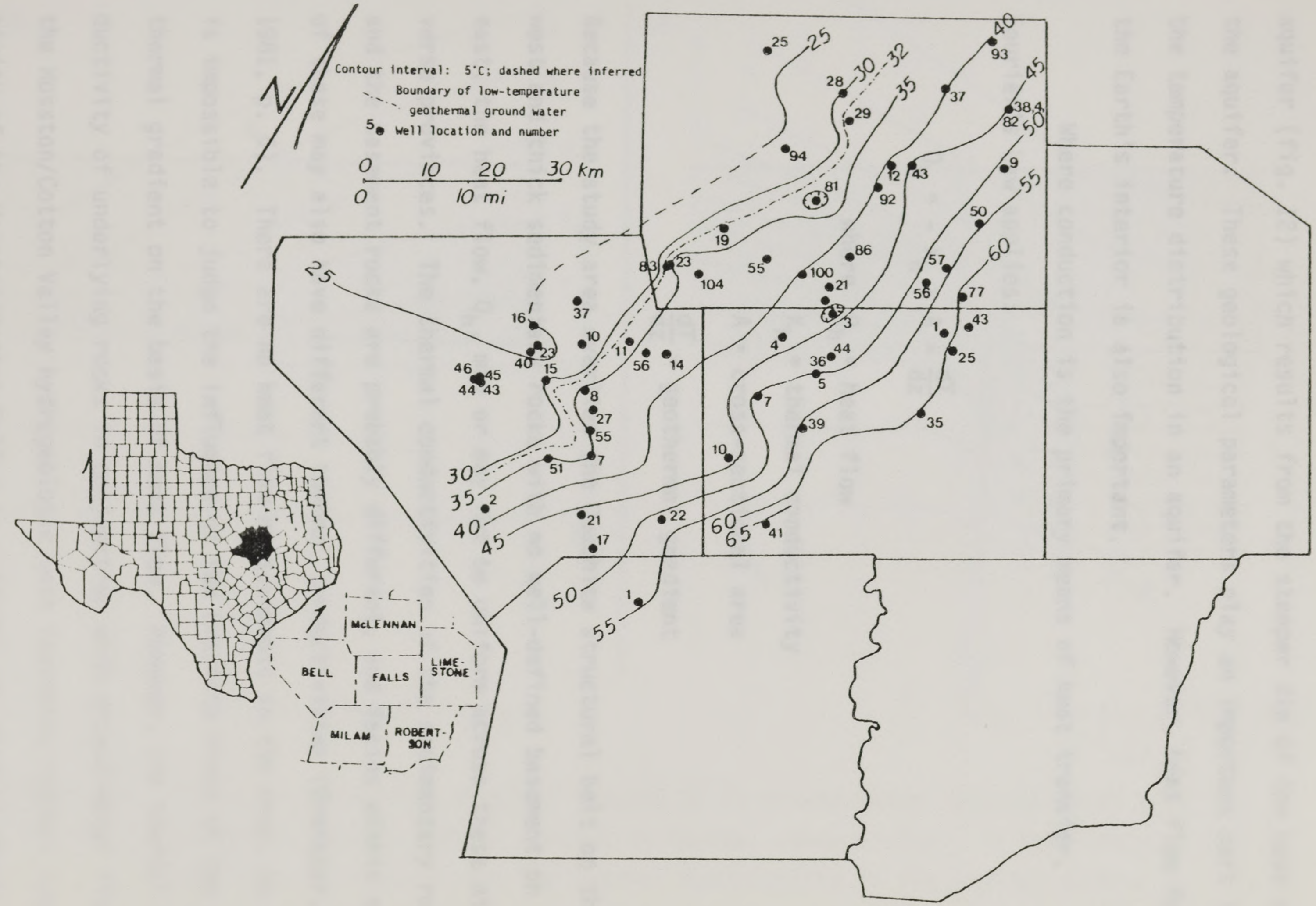


Figure 29: Distribution of water temperature in the Hosston/Cotton Valley hydrogeologic unit. Temperatures are based on well-head (production) temperatures.

aquifer (fig. 12) which results from the steeper dip of the base of the aquifer. These geological parameters play an important part in the temperature distribution in an aquifer. However, heat flow from the Earth's interior is also important.

Where conduction is the primary means of heat transfer, Fourier's Law applies:

$$Q_h = - K_h \times A \times \frac{dT}{dz}$$

where Q_h = heat flow

K_h = thermal conductivity

A = cross-sectional area

$\frac{dT}{dz}$ = geothermal gradient

Because the study area overlies the Ouachita structural belt on the west and thick sedimentary rocks with no well-defined basement on the east, the heat flow, Q_h, may or may not be uniform across these diverse provinces. The thermal conductivities of the sedimentary rocks and the basement rocks are probably different, and facies within each of these may also have different thermal conductivities (Gretener, 1981, p. 6). There are no heat flow measurements in the area, so it is impossible to judge the influence of the Ouachita hinge on the geothermal gradient on the basis of heat flow. However, the thermal conductivity of underlying rocks in conjunction with ground-water flow in the Hosston/Cotton Valley hydrogeologic unit (assuming thermal conductivity of the Hosston/Cotton Valley is uniform) may distort the heat flow (fig. 30). Cold, recharging ground water acts as a heat sink and

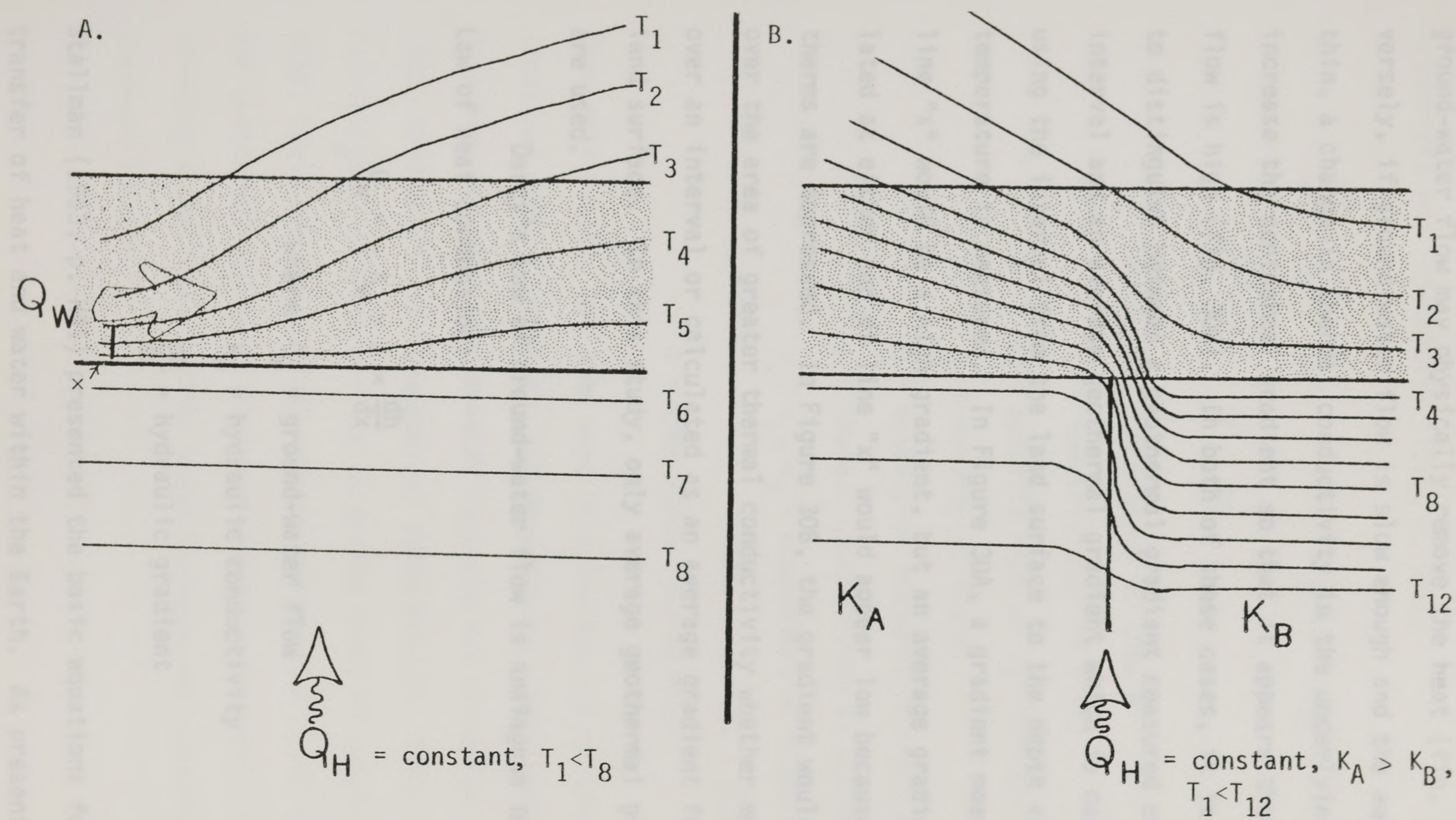


Figure 30: Change in geothermal gradient because of A) ground-water recharge depressing isotherms, and B) lateral changes in thermal conductivity. In both cases, heat flow is constant and the thermal conductivity in the aquifer being measured (stippled area) is constant, yet the geothermal gradient is not.

ground-water flow may physically remove the heat (fig. 30A). Conversely, if ground-water flow is slow enough and the aquifer is thin, a change in thermal conductivity in the underlying rocks may increase the geothermal gradient so that it appears that heat flow is high (fig. 30B). In both of these cases, it is important to distinguish between a geothermal gradient measured over a small interval and an average geothermal gradient which is calculated using the interval from the land surface to the depth at which the temperature is measured. In Figure 30A, a gradient measured along line "x" would be a high gradient, but an average gradient calculated at either end of line "x" would appear low because the isotherms are depressed. In Figure 30B, the gradient would be high over the area of greater thermal conductivity whether measured over an interval or calculated as an average gradient from the land surface. In this study, only average geothermal gradients are used.

Darcy's Law of ground-water flow is analagous to Fourier's Law of heat conduction:

$$Q_w = - K_w \times A \times \frac{dh}{dx}$$

where Q_w = ground-water flow

K_w = hydraulic conductivity

$\frac{dh}{dx}$ = hydraulic gradient

Stallman (1963, p. H41) presented the basic equations for simultaneous transfer of heat and water within the Earth. As presented by

Bredehoeft and Papadopulos (1965, p. 325):

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} - \frac{c_0 \rho_0}{K} \times \{ \frac{\partial(v_x T)}{\partial x} + \frac{\partial(v_y T)}{\partial y} +$$

$$\frac{\partial(v_z T)}{\partial z} \} = \frac{c\rho}{K} \times \frac{\partial T}{\partial t}$$

where T = temperature at time t

c_0 = specific heat of fluid

c = specific heat of solid-fluid complex

ρ_0 = density of fluid

ρ = density of solid-fluid complex

K = thermal conductivity of solid-fluid complex

v_x, v_y, v_z = components of fluid velocity in the x, y, and z directions

t = time since flow started

This relationship has been used to calculate ground-water velocities (Stallman, 1963; Bredehoeft and Papadopulos, 1965; Sorey, 1971), to determine areas of ground-water recharge and discharge (Donaldson, 1962; Bredehoeft and Papadopulos, 1965; Parsons, 1970; Domenico and Palciauskas, 1973) as well as to define areas of geopressure (Jones, 1969; Lewis and Rose, 1970). Ground-water flow could also influence the geothermal regime in that hot water from a deeper flow system invading a shallower aquifer would increase the measured geothermal gradient locally.

In the study area, the type and distribution of data preclude an exhaustive quantitative analysis of the geothermal regime. Some relationships are evident, however, and by examining the distribution of geothermal gradients in the Hosston/Cotton Valley in light of the geology and hydrology of the aquifer, and by comparing these with gradients in geologic formations of relatively constant composition above and below the aquifer, a tentative geothermal setting will be constructed. The Glen Rose Formation (Forgotson, 1957, p. 2356-2359) and the Smackover Formation (Swain, 1949, p. 1215-1219) qualify as units of relatively uniform composition and are useful for comparison with the Hosston/Cotton Valley. The Paleozoic-age formations, although less well known, also prove useful for this examination of geothermal gradients and geothermal regime.

Types of Data

Bottom-hole temperatures or maximum-recorded temperatures compiled from geophysical logs comprise the data base (Appendix II), along with a temperature survey from Falls County well no. 35, the T.H.S. Memorial Hospital geothermal well. Temperatures of water produced from the formation are also part of the data base, and are especially important in the western half of the study area where geophysical logs with temperatures are relatively scarce.

The unit used for geothermal gradient in this report is the conventional one of °C/km. However, as is evident in comparing gradients from different formations, shown below, these gradients should not be used to extrapolate formation temperatures long distances from where the gradient was measured. The geothermal gradient calculated from bottom-hole or produced-water temperature is applicable only to the point at which it was measured, or to the aquifer in which is was measured if that aquifer is of relatively uniform composition.

Geothermal Gradient Distribution

Geothermal gradients form a distinctive pattern in the study area (figs. 31-33). The gradients range from less than 25°C/km to more than 40°C/km. The Geothermal Gradient Map of North America (1976) shows gradients in the Gulf Coast Basin ranging from less than 25°C/km to more than 33°C/km, which is comparable but slightly less than those in the study area. On the same map, regional gradients trend approximately parallel to the strike of formations and structures. Similarly, in the Hosston/Cotton Valley in the study area, higher gradients within the Balcones and Mexia Fault Zones (figs. 1 and 7) are flanked by areas of much lower gradients (fig. 31). The area of highest gradients parallels the trend of the Ouachita structural belt and the Balcones Fault Zone in Bell and McLennan Counties. Geothermal gradients in the downdip part of the Hosston/Cotton Valley are relatively constant (around 27.5°C/km) although in central Limestone County an area of slightly higher gradients crosses the Mexia Fault Zone and extends southeastward or approximately perpendicular

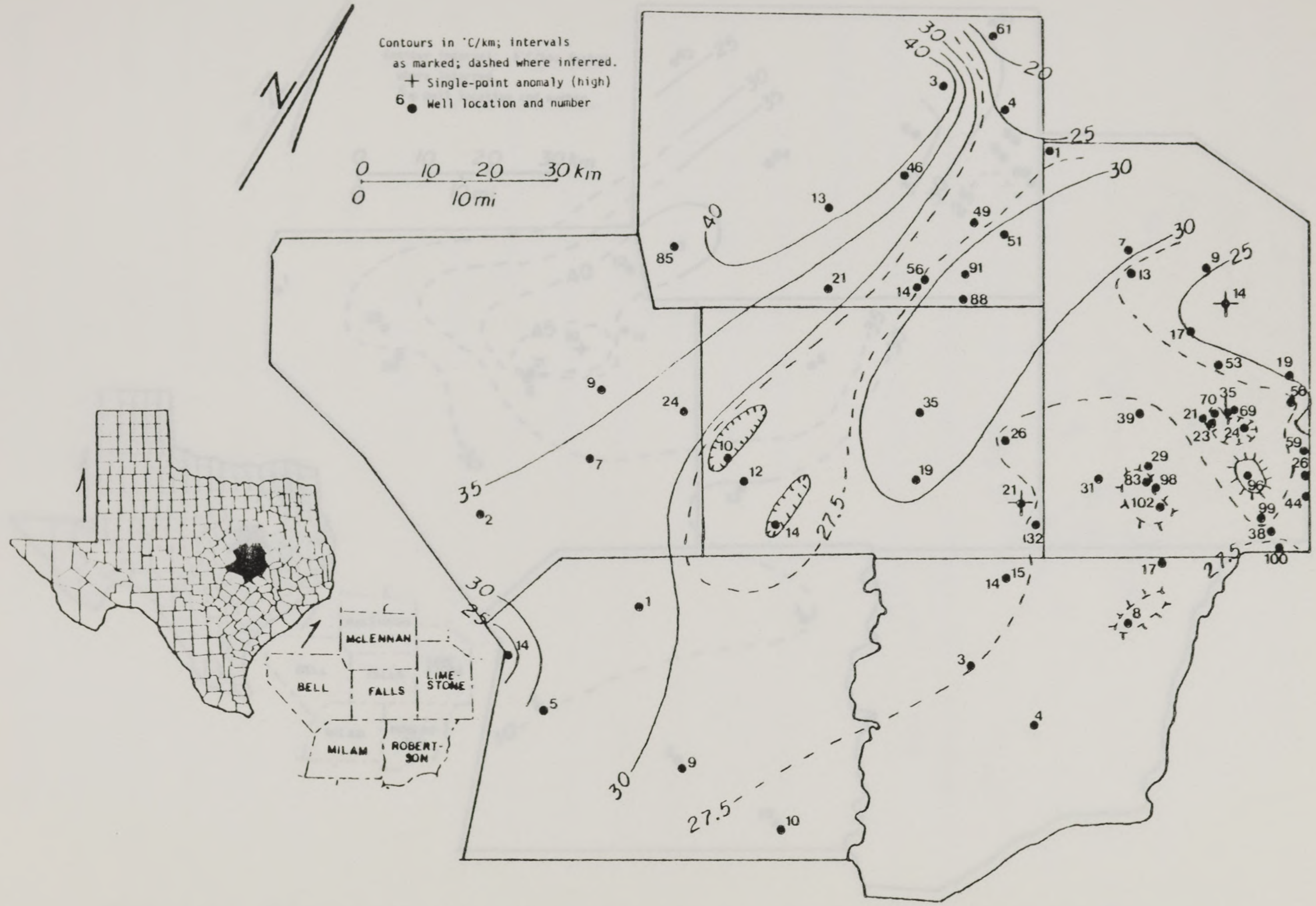


Figure 31: Distribution of geothermal gradients calculated from bottom-hole temperatures in the Hosston/Cotton Valley hydrogeologic unit.

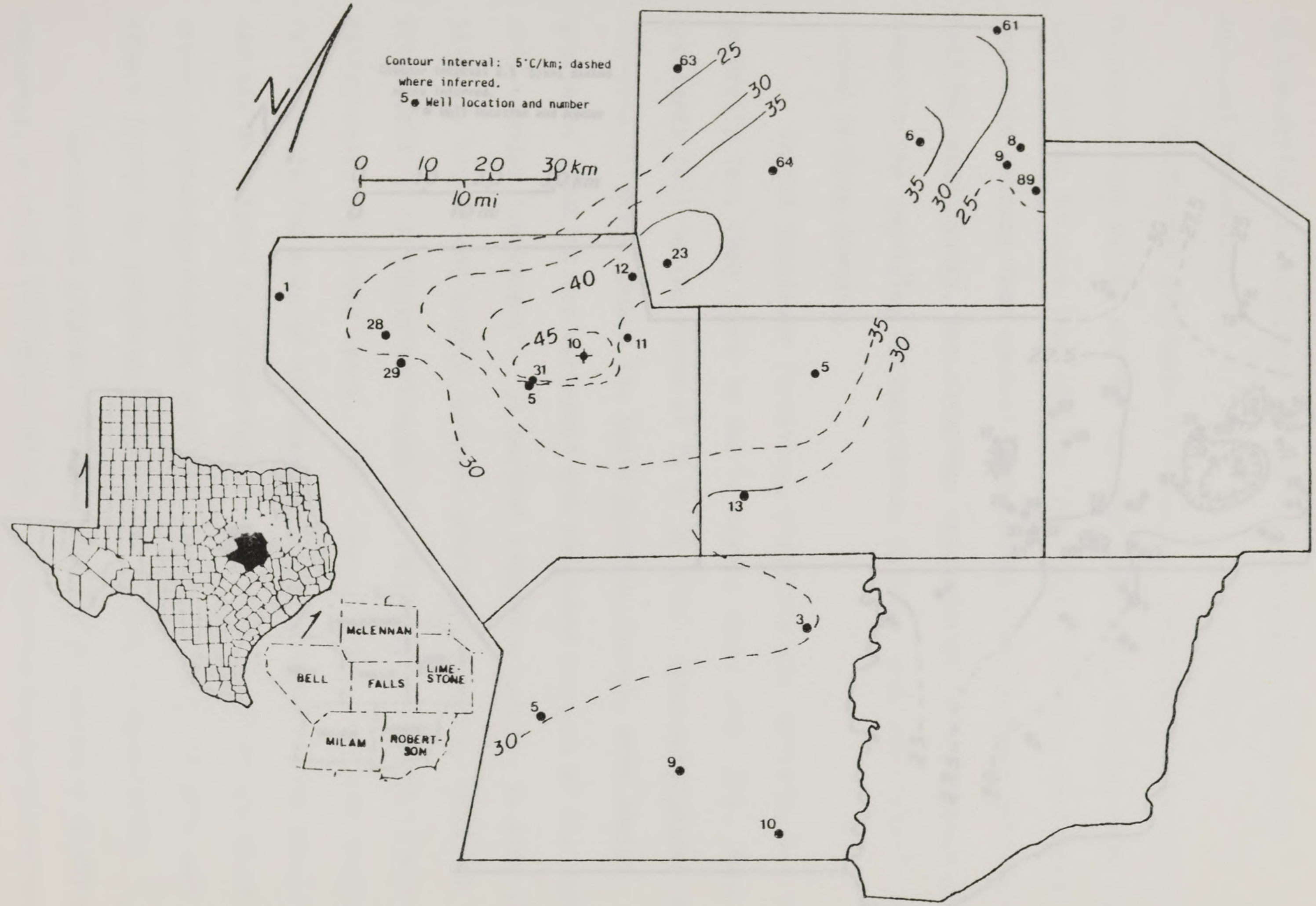


Figure 32: Distribution of geothermal gradients calculated from bottom-hole temperatures in Paleozoic-age rocks.

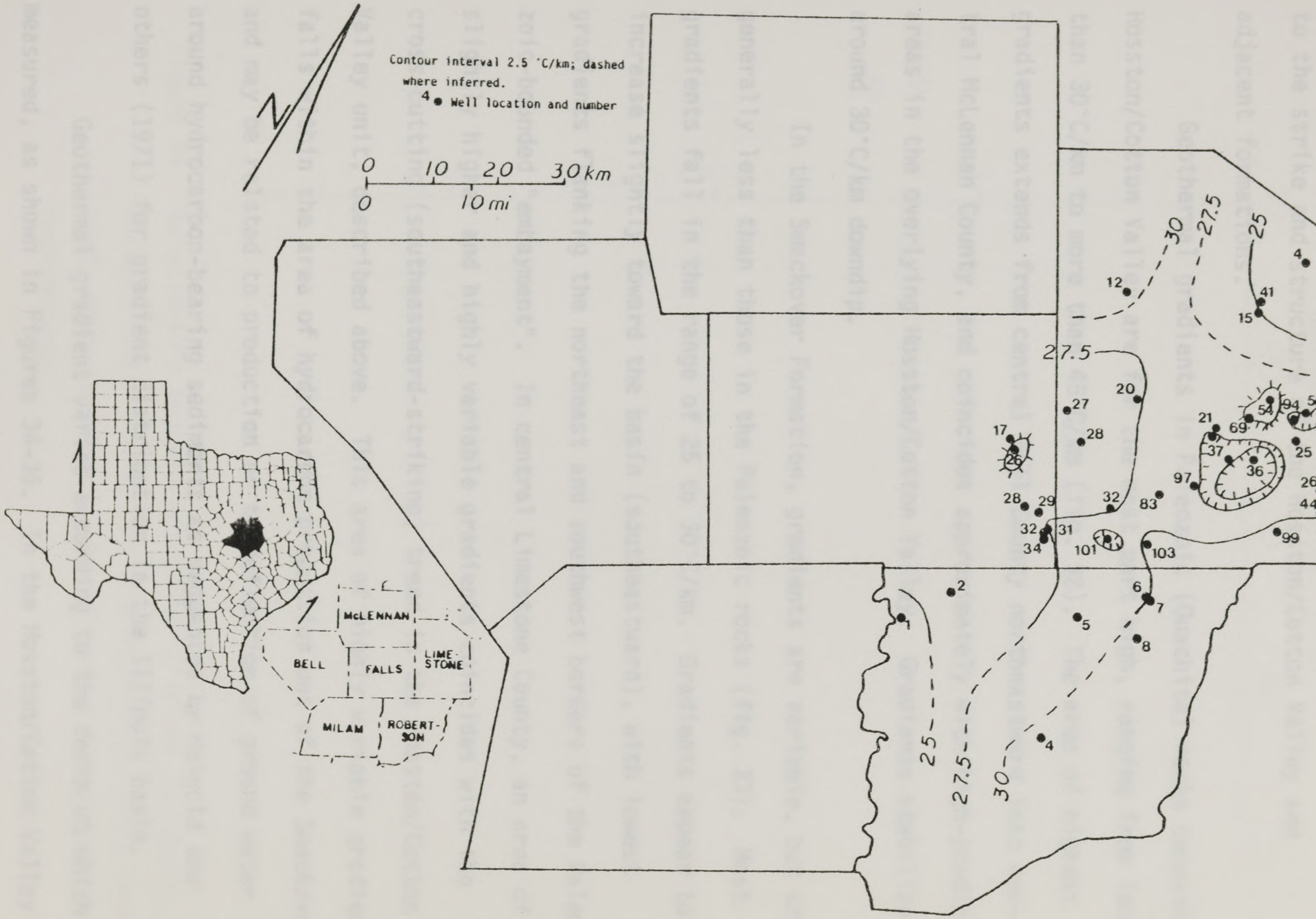


Figure 33: Distribution of geothermal gradients calculated from bottom-hole temperatures in the Smackover Formation.

to the strike and structure of the Hosston/Cotton Valley and adjacent formations.

Geothermal gradients in Paleozoic (Ouachita) rocks beneath the Hosston/Cotton Valley are for the most part high, ranging from less than 30°C/km to more than 45°C/km (fig. 32). The area of highest gradients extends from central Bell County northeastward into central McLennan County, and coincides approximately with high-gradient areas in the overlying Hosston/Cotton Valley. Gradients stabilize around 30°C/km downdip.

In the Smackover Formation, gradients are variable, but are generally less than those in the Paleozoic rocks (fig. 33). Most gradients fall in the range of 25 to 30°C/km. Gradients appear to increase slightly toward the basin (southeastward), with lowest gradients flanking the northeast and southwest borders of the Paleozoic-bounded "embayment". In central Limestone County, an area of slightly higher and highly variable gradients coincides with the cross-cutting (southeastward-striking) trend in the Hosston/Cotton Valley unit, described above. This area of highly variable gradients falls within the area of hydrocarbon production out of the Smackover, and may be related to production or to deflection of ground water around hydrocarbon-bearing sediments as suggested by Heigold and others (1971) for gradient distribution in the Illinois basin.

Geothermal gradient varies according to the depth at which it is measured, as shown in Figures 34-36. In the Hosston/Cotton Valley hydrogeologic unit (fig. 34), at depths greater than 2 km geothermal

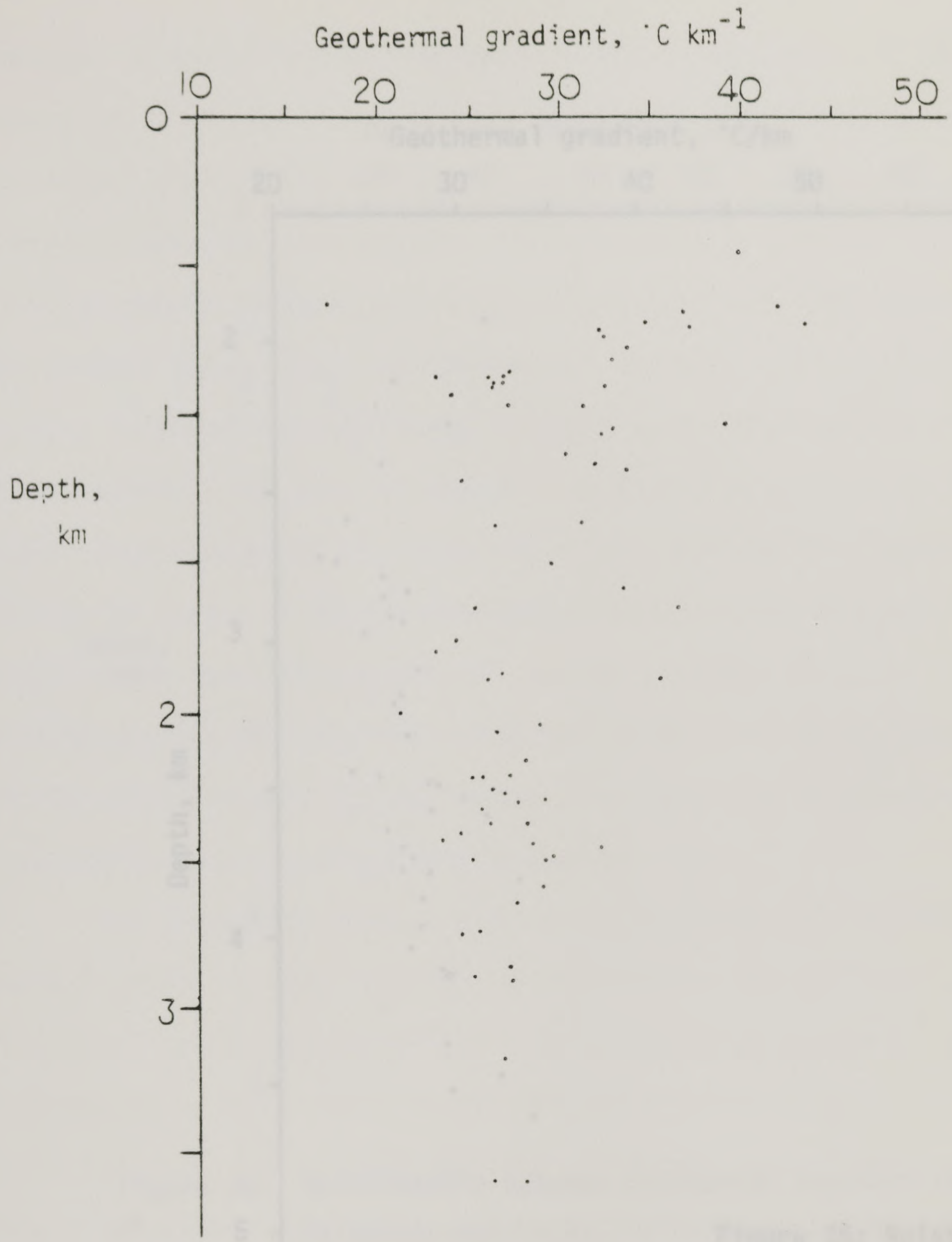


Figure 34: Relationship between geothermal gradient and depth, Hosston/Cotton Valley hydrogeologic unit, Falls County study area. Gradients are calculated from bottom-hole temperatures.

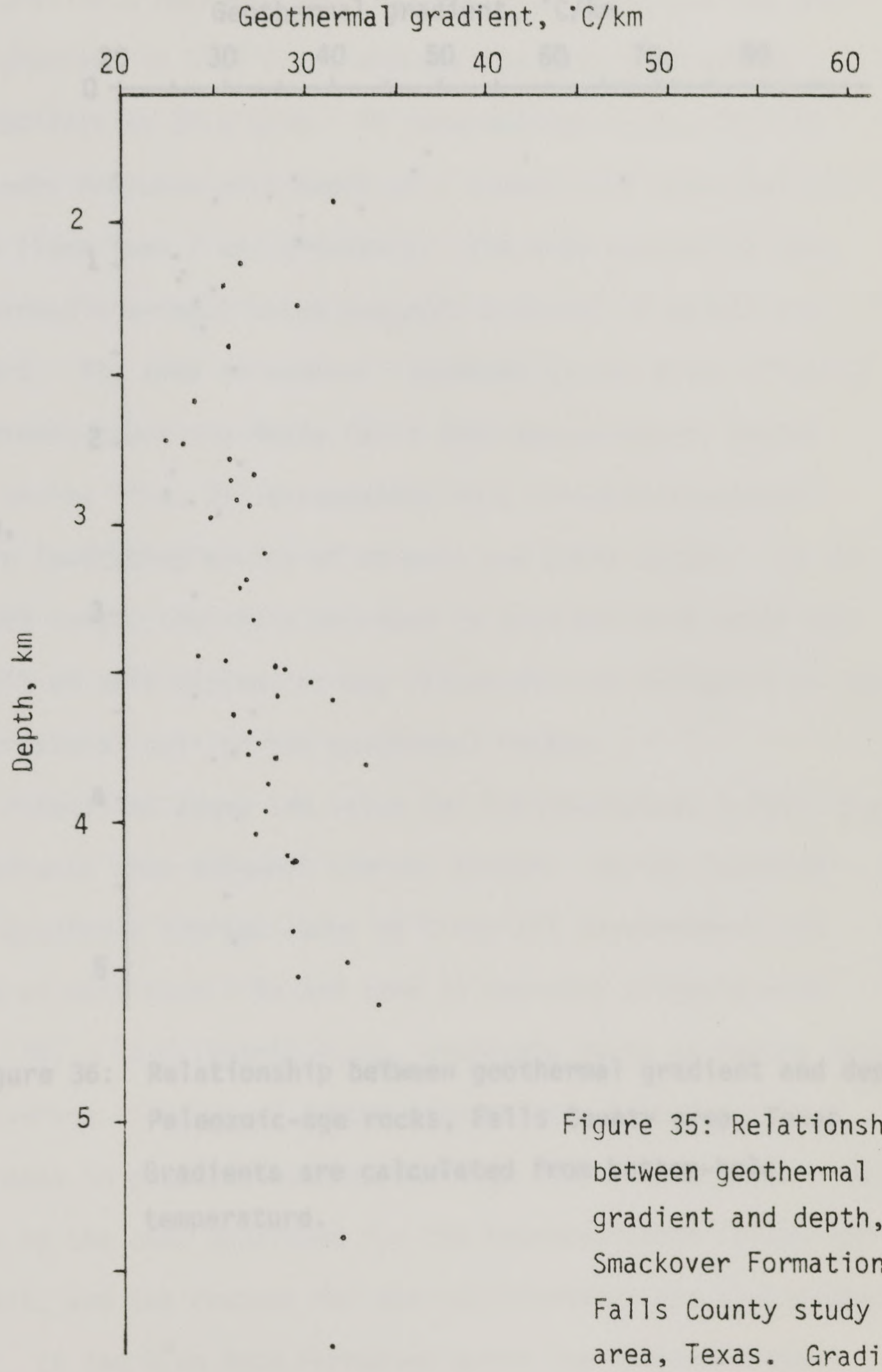


Figure 35: Relationship between geothermal gradient and depth, Smackover Formation, Falls County study area, Texas. Gradients are calculated from bottom-hole temperature.

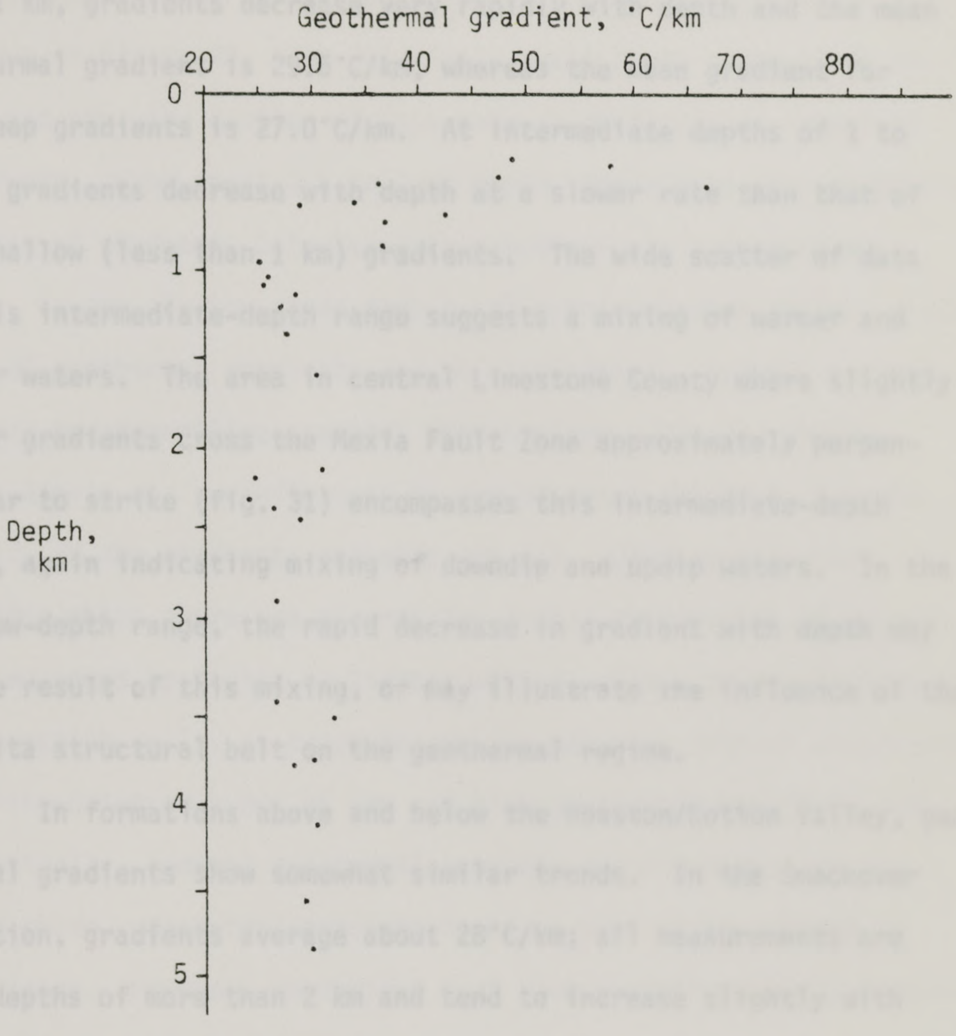


Figure 36: Relationship between geothermal gradient and depth, Paleozoic-age rocks, Falls County area, Texas. Gradients are calculated from bottom-hole temperature.

gradient is approximately constant with depth; at depths of less than 1 km, gradients decrease very rapidly with depth and the mean geothermal gradient is 29.6°C/km, whereas the mean gradient for the deep gradients is 27.0°C/km. At intermediate depths of 1 to 2 km, gradients decrease with depth at a slower rate than that of the shallow (less than 1 km) gradients. The wide scatter of data in this intermediate-depth range suggests a mixing of warmer and cooler waters. The area in central Limestone County where slightly higher gradients cross the Mexia Fault Zone approximately perpendicular to strike (fig. 31) encompasses this intermediate-depth range, again indicating mixing of downdip and updip waters. In the shallow-depth range, the rapid decrease in gradient with depth may be the result of this mixing, or may illustrate the influence of the Ouachita structural belt on the geothermal regime.

In formations above and below the Hosston/Cotton Valley, geothermal gradients show somewhat similar trends. In the Smackover Formation, gradients average about 28°C/km; all measurements are from depths of more than 2 km and tend to increase slightly with depth (fig. 35). In Paleozoic rocks, gradients taken at depths less than 1 km average 41°C/km; at depths greater than 1 km there is a slight increase in gradient with depth (fig. 36). These relationships are similar to the ones described for the Hosston/Cotton Valley hydrogeologic unit, and the reasons for the relationships are also probably similar. In the Glen Rose Formation above the Hosston/Cotton Valley, the data are few, but similar trends may exist.

The relationship between geothermal gradient calculated from produced-water temperatures and depth in the Hosston/Cotton Valley is shown in Figure 37. The relatively small depth range (0.25 to 1 km) and the wide scatter of data make it difficult to interpret any trends. From about 0.5 to 1 km depth, these data are comparable to those of gradients calculated from bottom-hole temperatures.

In the shallow (less than 1 km) Hosston/Cotton Valley, a wide range of geothermal gradients may be encountered. Several mechanisms may be controlling gradient distribution. The few shallow, low gradients may be influenced by ground-water recharge, but the majority of the gradients probably are not. Differential heat flow (for which there are no existing data); restriction of ground-water movement by faults or leakage of hot, deep water up faults; or convection cells, as suggested by the somewhat regular alteration of strike-oriented zones of low and high geothermal gradients, can, theoretically, control geothermal gradient distribution. As mentioned above, geothermal-gradient highs do seem to be related to fault zones. However, convective heat flow as influenced by ground-water flow may also be important.

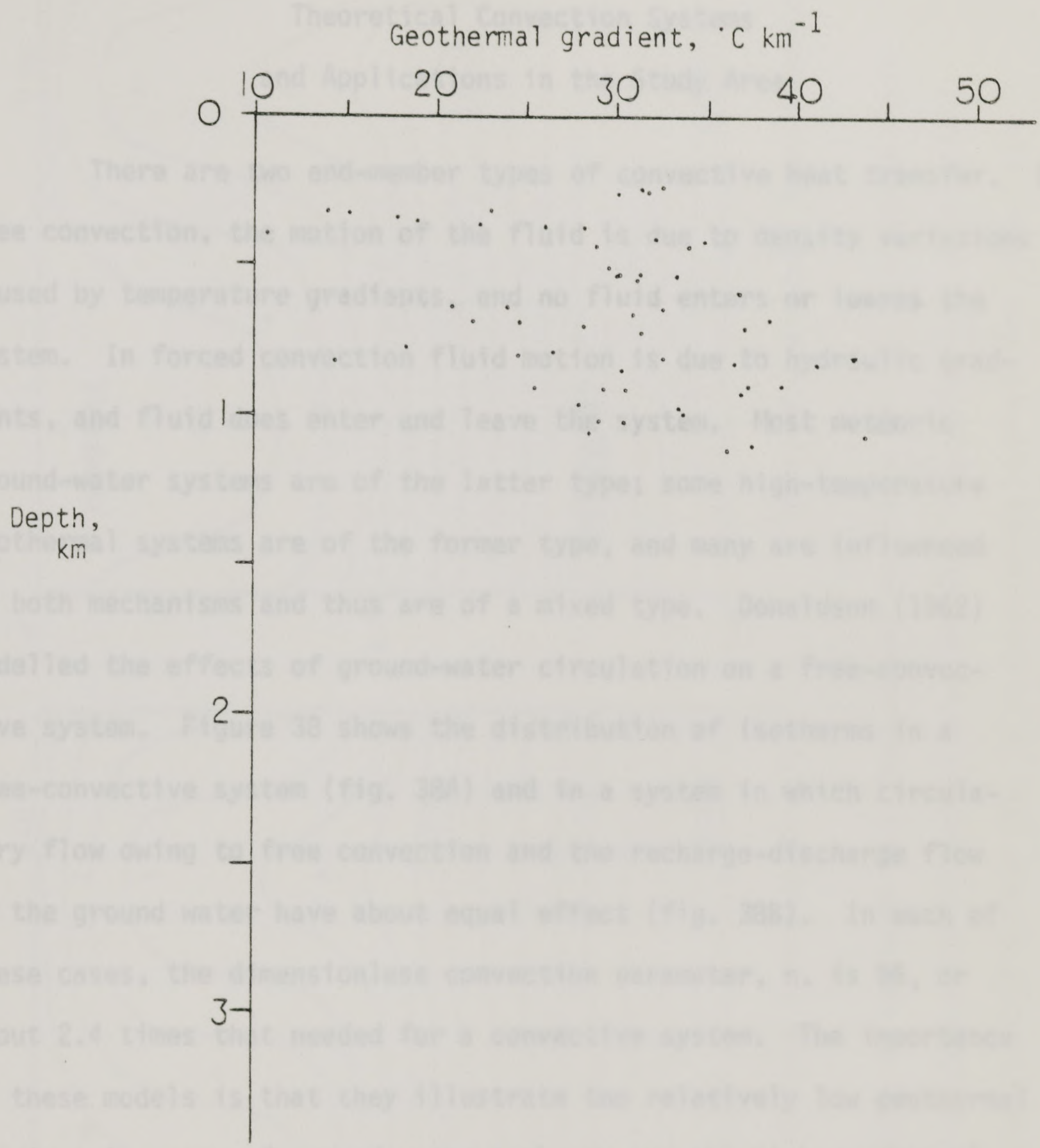


Figure 37: Relationship between geothermal gradient (calculated from produced-water temperatures) and depth, Hosston/Cotton Valley hydrogeologic unit, Falls County study area, Texas.

Theoretical Convection Systems and Applications in the Study Area

There are two end-member types of convective heat transfer. In free convection, the motion of the fluid is due to density variations caused by temperature gradients, and no fluid enters or leaves the system. In forced convection fluid motion is due to hydraulic gradients, and fluid does enter and leave the system. Most meteoric ground-water systems are of the latter type; some high-temperature geothermal systems are of the former type, and many are influenced by both mechanisms and thus are of a mixed type. Donaldson (1962) modelled the effects of ground-water circulation on a free-convective system. Figure 38 shows the distribution of isotherms in a free-convective system (fig. 38A) and in a system in which circulatory flow owing to free convection and the recharge-discharge flow of the ground water have about equal effect (fig. 38B). In each of these cases, the dimensionless convection parameter, η, is 96, or about 2.4 times that needed for a convective system. The importance of these models is that they illustrate the relatively low geothermal gradient in areas of ground-water recharge and the high geothermal gradient in areas of ground-water discharge. Domenico and Palciauskas (1973) also looked at forced convection in a ground-water basin and found that the basin depth-to-length ratio is important in determining whether conduction or convection dominates the geothermal regime.

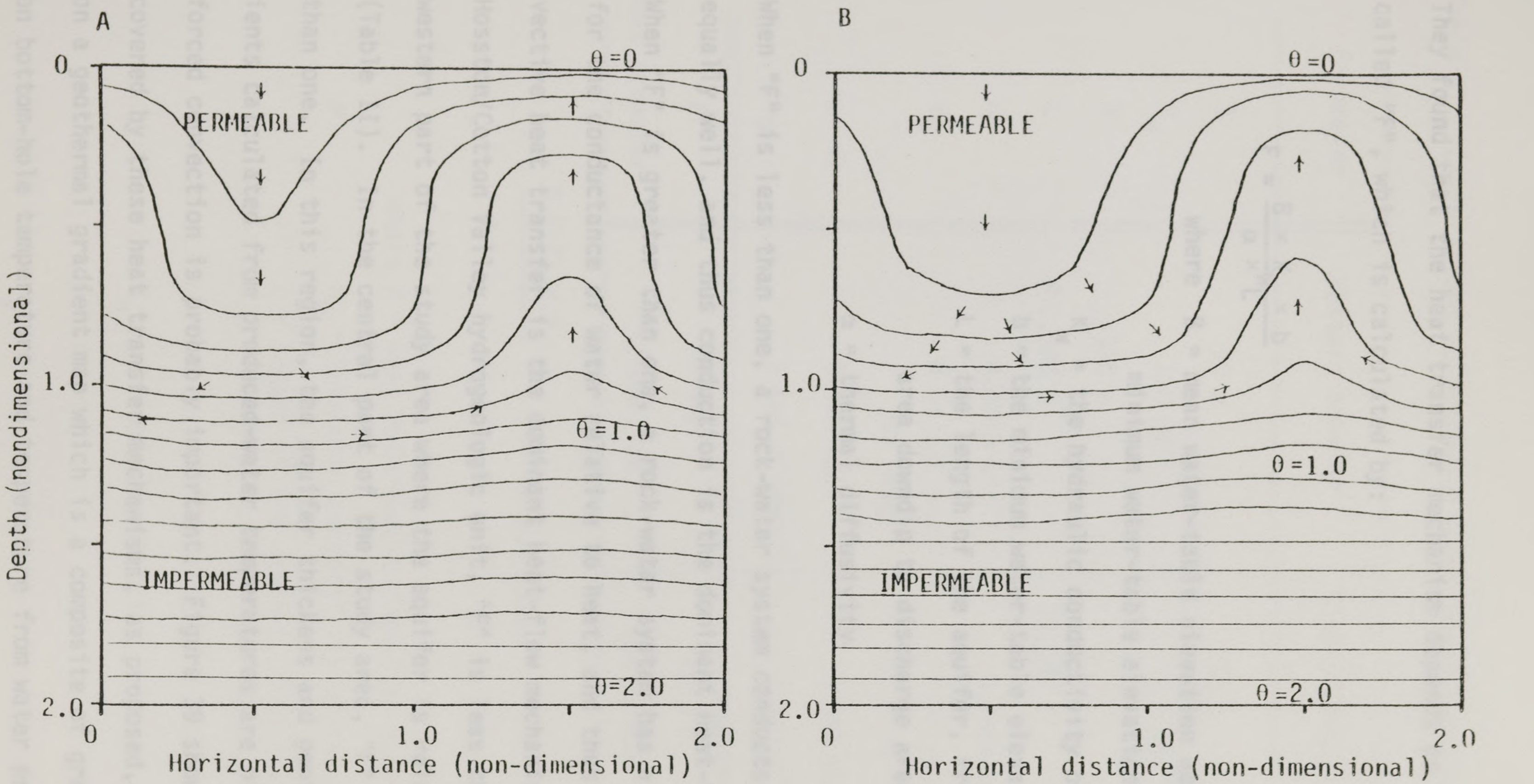


Figure 38: Distribution of isotherms in a free-convection system (A) and in a system where recharge-discharge flow of ground water and free convection have equal effect on temperature distribution (B). θ is temperature isotherm and arrows show direction of ground water movement (modified from Donaldson, 1962).

They found that the heat transfer mechanism depends on a factor, here called "F", which is calculated by:

$$F = \frac{B \times K_w \times b}{\alpha \times L}$$

where B = mean water-table elevation above the minimum water-table elevation

K_w = the hydraulic conductivity of the aquifer

b = the minimum water-table elevation

L = the length of the aquifer, from recharge area downdip to discharge area

α = thermal diffusivity

When "F" is less than one, a rock-water system conducts heat and water equally well, and thus conduction is the dominant heat-flow mechanism. When "F" is greater than one, a rock-water system has a high capacity for the conductance of water relative to heat, and thus forced-convective heat transfer is the dominant heat-flow mechanism. In the Hosston/Cotton Valley hydrogeologic unit, "F" is less than one in the western part of the study area where the aquifer is relatively thin (Table II). In the central part of the study area, "F" is greater than one. In this region, the aquifer thickens and geothermal gradients calculated from produced-water temperatures are high, and forced convection is probably important. Figure 39 shows the areas covered by these heat transfer mechanisms, as proposed, superimposed on a geothermal gradient map which is a composite of gradients based on bottom-hole temperature and temperature from water produced from

Table II: Calculations to determine heat-transfer mechanism.

Parameter	Western aquifer	Central aquifer
B	50 m	50 m
K_w	1.0 md^{-1}	1.0 md^{-1}
b	150 m	
L	282,000 m	25,000 m
α	0.0868 m^2d^{-1}	0.0868 m^2d^{-1}
K_h	0.01 cal sec^{-1} $cm^{-1}deg^{-1}$	0.01 cal sec^{-1} $cm^{-1}deg^{-1}$
ρ	0.995 kgl^{-1}	0.995 kgl^{-1}
c_p	1 cal $g^{-1}deg^{-1}$	1 cal $g^{-1}deg^{-1}$
F	0.306	26.3
Heat transfer	Conduction	Convection

$$F = \frac{B \times K_w \times b}{\alpha \times L} , \quad = \frac{K_h}{\rho \times c_p}$$

where B = mean water-table elevation above b

K_w = hydraulic conductivity of the aquifer

L = length of the aquifer, from recharge area downdip to discharge area

α = thermal diffusivity

K_h = thermal conductivity

ρ = density

c_p = heat capacity

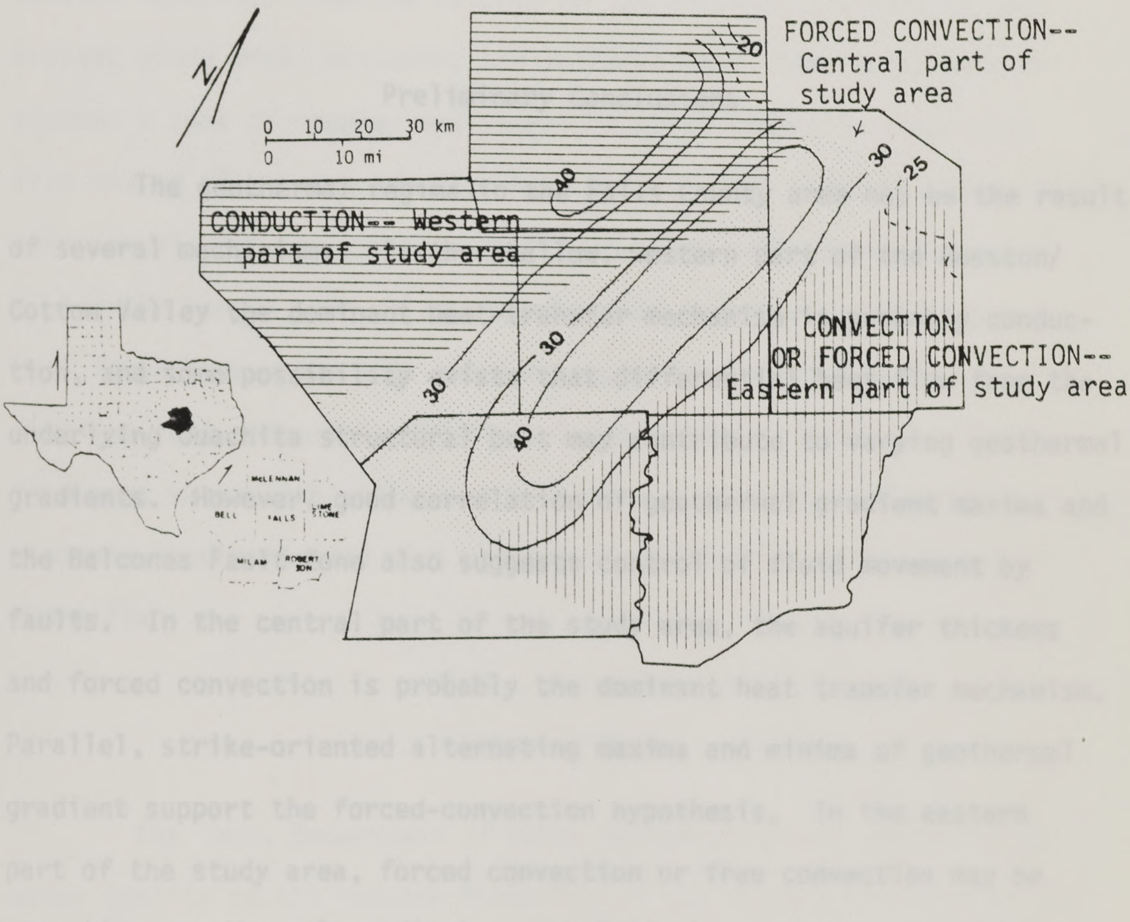


Figure 39: Composite geothermal gradient map and areas of conductive and convective heat transfer. Gradients are in °C/km.

the wells. In the eastern part of the study area, "F" is difficult to determine since the lateral extent of the aquifer is not known. Probably convection and perhaps forced convection are important in the deep basin, judging by the much greater aquifer thickness.

Preliminary Conclusions

The geothermal regime in the Falls County area may be the result of several mechanisms. In the shallow, western part of the Hosston/Cotton Valley the dominant heat-transfer mechanism is probably conduction, and some possibility exists that differential heat flow from the underlying Ouachita structural belt may contribute to varying geothermal gradients. However, good correlation of geothermal gradient maxima and the Balcones Fault Zone also suggests control of fluid movement by faults. In the central part of the study area, the aquifer thickens and forced convection is probably the dominant heat transfer mechanism. Parallel, strike-oriented alternating maxima and minima of geothermal gradient support the forced-convection hypothesis. In the eastern part of the study area, forced convection or free convection may be operating; geothermal gradients are relatively constant. Some high anomalies are associated with the Mexia Fault Zone, suggesting upward leakage of deep, hot brines along the faults.

WATER CHEMISTRY

Previous Studies

Henningsen (1962) discussed the ground-water chemistry of the Hosston Formation from the outcrop to the northwestern half of the present study area, excluding the Balcones Fault Zone which he considered a zone of complex and anomalous water chemistry resulting from mixing of Hosston and Glen Rose water. Hall (1976) examined the relationship between hydrochemical facies and sedimentary facies of a slightly larger area which includes that examined by Henningsen. Hall found that water with calcium, magnesium and bicarbonate as dominant ions coincided with fluvial depositional facies he identified, and water with sodium and bicarbonate or sodium and sulfate as dominant ions coincided with the deltaic depositional facies he identified.

Types of Data

The Texas Department of Water Resources (TDWR) monitors the water quality of the Hosston Formation in the study area; most of the data used in this part of the investigation come from their files. Chemical analyses from 118 wells in Bell, Falls, McLennan and Milam Counties comprise the data base provided by the TDWR; more than one chemical analysis may have been reported for each well. Figure 40 shows the location of each of these wells and Appendix VI contains a

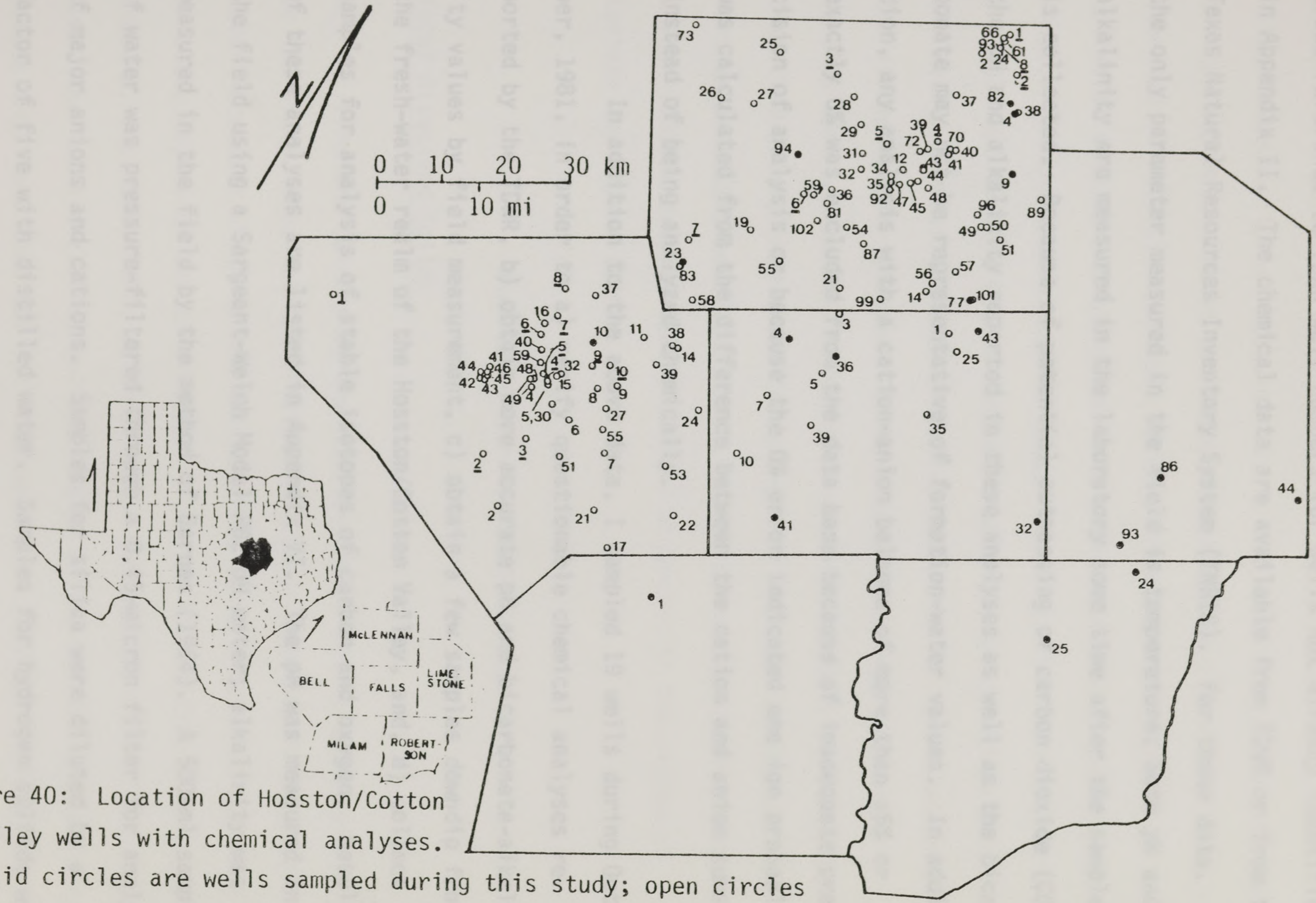


Figure 40: Location of Hosston/Cotton Valley wells with chemical analyses. Solid circles are wells sampled during this study; open circles indicate chemical analysis is on file at TDWR. Underlined well numbers are cross-referenced in Appendix VI while others are cross-referenced in Appendix II.

cross reference to TDWR well numbers for wells not already identified in Appendix II. The chemical data are available from TDWR or from the Texas Natural Resources Inventory System (TNRIS). For these data, the only parameter measured in the field is temperature; both pH and alkalinity are measured in the laboratory some time after the sample is collected. Because of potential outpassing of carbon dioxide (CO_2), the pH and alkalinity reported in these analyses as well as the bicarbonate may not be representative of formation-water values. In addition, any analysis with a cation-anion balance of more than ±5% or exactly 0% was excluded from the data base because of inadequate precision of analysis or because the 0% error indicated one ion probably was calculated from the difference between the cation and anion sums instead of being analyzed chemically.

In addition to the above data, I sampled 19 wells during October, 1981, in order to a) verify questionable chemical analyses reported by the TDWR, b) obtain more accurate pH and bicarbonate-alkalinity values by field measurement, c) obtain a few samples downdip from the fresh-water realm of the Hosston/Cotton Valley, and, d) collect samples for analysis of stable isotopes of carbon and oxygen. Results of these analyses are listed in Appendix VI. The pH was measured in the field using a Sargeant-Welch Model PBL pH meter; alkalinity was measured in the field by the method of Barnes (1964). A 500-ml sample of water was pressure-filtered through a 0.45-micron filter for analysis of major anions and cations. Samples for silica were diluted by a factor of five with distilled water. Samples for hydrogen sulfide were preserved in the field by the addition of 5 ml cadium acetate.

Conductivity and water temperature were also measured at the well site; conductivity was measured with a YSI Model 33 Salinity-Conductivity-Temperature meter and water temperature was measured using a standard (0°-100°C) laboratory mercury thermometer. A 125-ml, untreated sampled was collected in a glass bottle with ground-glass stopper for analysis of stable oxygen isotopes; in a similar container, a sample was treated with a saturated solution of strontium chloride and with a 6-molar solution of sodium hydroxide for later analysis of the stable carbon isotopes. $SrCO_3$ precipitates from the latter samples were washed five times in an argon atmosphere with CO_2-free distilled water, then dried in an argon or nitrogen atmosphere, and further processed according to the method of McCrea (1950). The oxygen-isotope samples were processed according to the method of Epstein and Mayeda (1953).

General Trends in Dissolved Ions

Total Dissolved Solids

From the outcrop of the Hosston/Cotton Valley hydrogeologic unit to the study area, the total dissolved solids content of the ground water increases slightly and the dominant ionic species change from calcium, magnesium and bicarbonate to sodium and sulfate (Henningsen, 1962, p. 16; Hall, 1976, p. 23-24). In the western half of the study area, the total dissolved solids content of the Hosston/Cotton Valley ranges from less than 600 mgl^{-1} to more than 2000 mgl^{-1} (fig. 41). The few data in the eastern part of the study area indicate the Hosston/

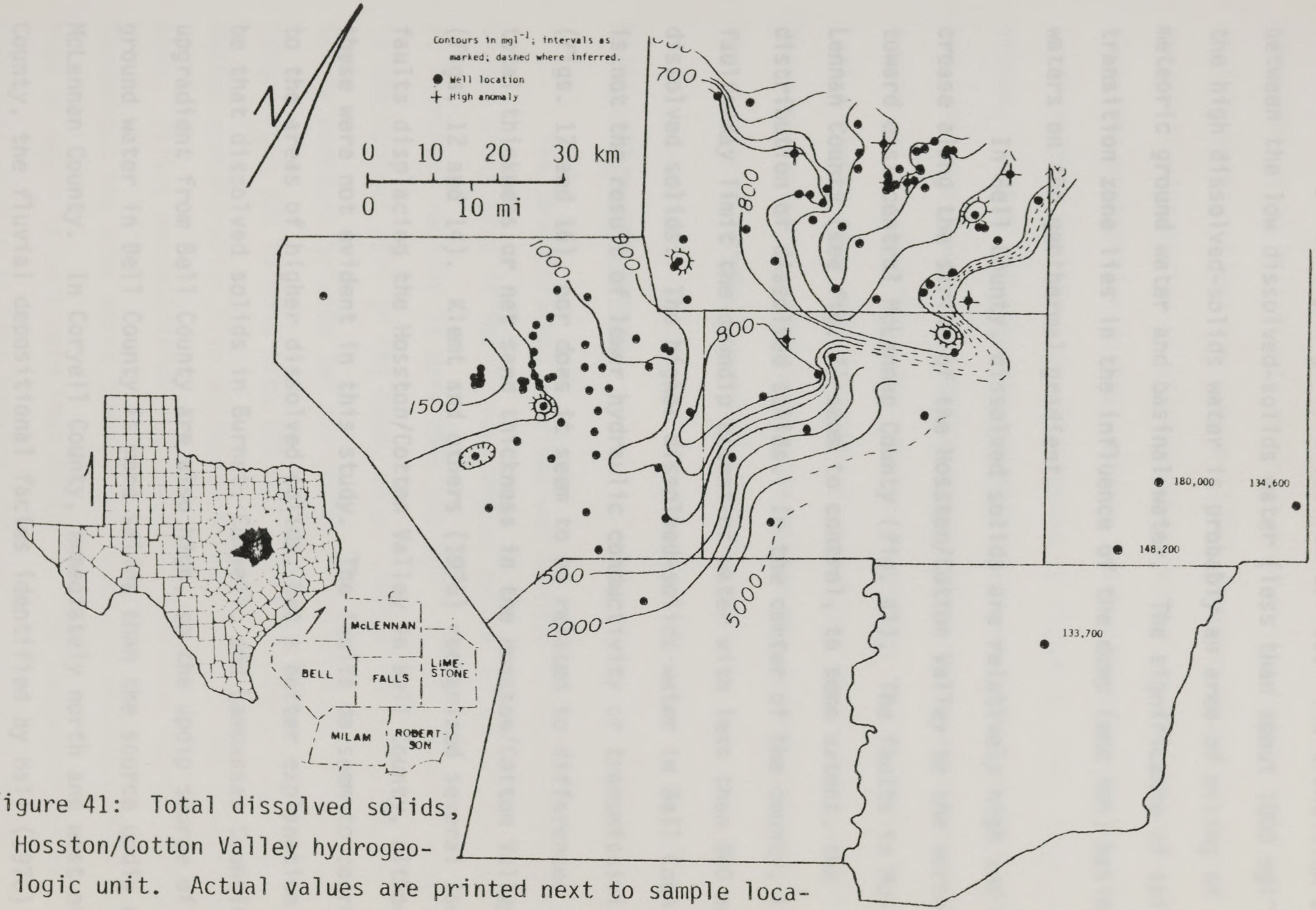


Figure 41: Total dissolved solids, Hosston/Cotton Valley hydrogeologic unit. Actual values are printed next to sample locations in the eastern half of the study area. The abrupt increase in dissolved solids in the central part of the study area marks the transition zone between meteoric and basinal water.

Cotton Valley is very high in dissolved solids. The transition zone between the low dissolved-solids water (less than about 1000 mgl^{-1}) and the high dissolved-solids water is probably an area of mixing of meteoric ground water and basinal water. The significance of this transition zone lies in the influence of the deep (and hot) basinal waters on the geothermal gradient.

In Bell County, dissolved solids are relatively high and decrease along the strike of the Hosston/Cotton Valley to the northeast toward east-central McLennan County (fig. 41). The faults in McLennan County (see fig. 7) seem to control, to some extent, the distribution of dissolved solids. In the center of the county, the faults may limit the downdip extent of water with less than 600 mgl^{-1} dissolved solids. The higher dissolved-solids water in Bell County is not the result of lower hydraulic conductivity or transmissivity (figs. 17 and 16), nor does it seem to be related to differences in total thickness or net sand thickness in the Hosston/Cotton Valley (figs. 12 and 14). Klemt and others (1975) recognized several long faults displacing the Hosston/Cotton Valley in Bell County, although these were not evident in this study. The faults do seem to correspond to the areas of higher dissolved solids, but a better explanation may be that dissolved solids in Burnet, Coryell, and Lampassas Counties upgradient from Bell County are also high, so the updip source of ground water in Bell County is more saline than the source updip of McLennan County. In Coryell County, immediately north and west of Bell County, the fluvial depositional facies identified by Hall (1976) do not contain calcium-magnesium-bicarbonate-type water, as he proposes for fluvial facies in his study area, but are similar to water downgradient in Bell County which is sodium-bicarbonate-chloride-sulfate water. Klemt and others (1975) propose that this is the result of dissolution of a "calcareous facies" in the Hosston. An alternate explanation is that surface water recharging the aquifer is of varying quality. As illustrated in Figure 5, total dissolved solids, sulfate and chloride concentrations are higher in the Leon and Lampassas Rivers than in the Brazos River where each crosses the outcrop of the Hosston. The problem of whether or not these chemical analyses are representative of historical water chemistry in these rivers and whether or not the rivers are in fact recharging the aquifer is beyond the scope of this study.

Major Cations and Anions

The concentration of dissolved calcium in the western half of the study area is fairly constant at around 10 mgl^{-1} (fig. 42). It increases rapidly to more than 200 mgl^{-1} in the transition zone in the central part of the study area. Sodium concentration is fairly constant between 200 and 300 mgl^{-1} in McLennan County, and ranges from 300 to more than 500 mgl^{-1} in Bell County (fig. 43). Sodium concentration also increases dramatically in the transition zone. Silica concentration, in contrast, increases fairly uniformly throughout the area where chemical analyses are available from less than 10 mgl^{-1} to just more than 30 mgl^{-1}. The concentration of dissolved sulfate is less regular (fig. 44), with most of Bell County

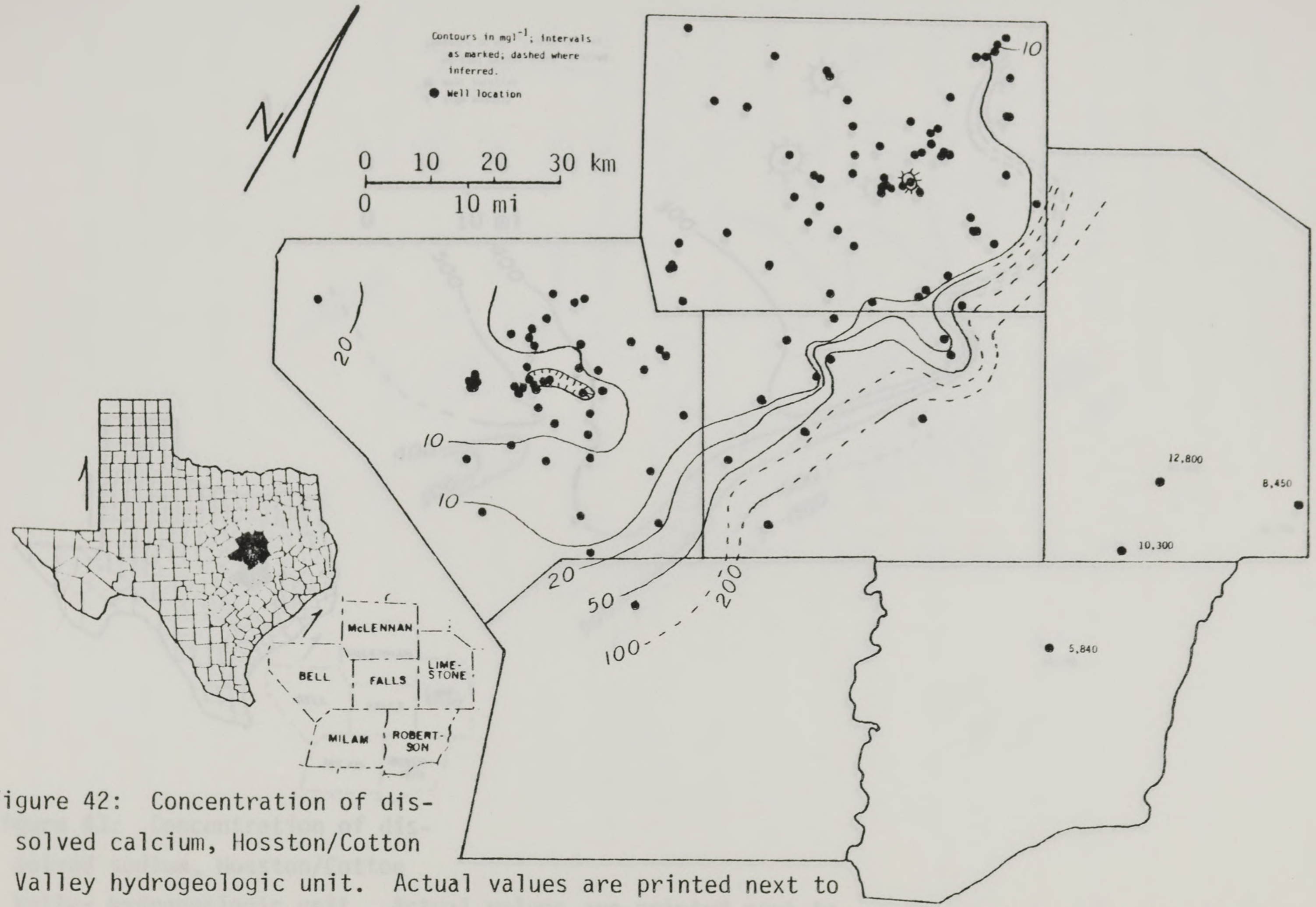


Figure 42: Concentration of dissolved calcium, Hosston/Cotton Valley hydrogeologic unit. Actual values are printed next to sample locations in the eastern half of the study area. Limited data in the east-central part of the study area prevent identification of the zone where calcium concentration increase to values typical of basinal water.

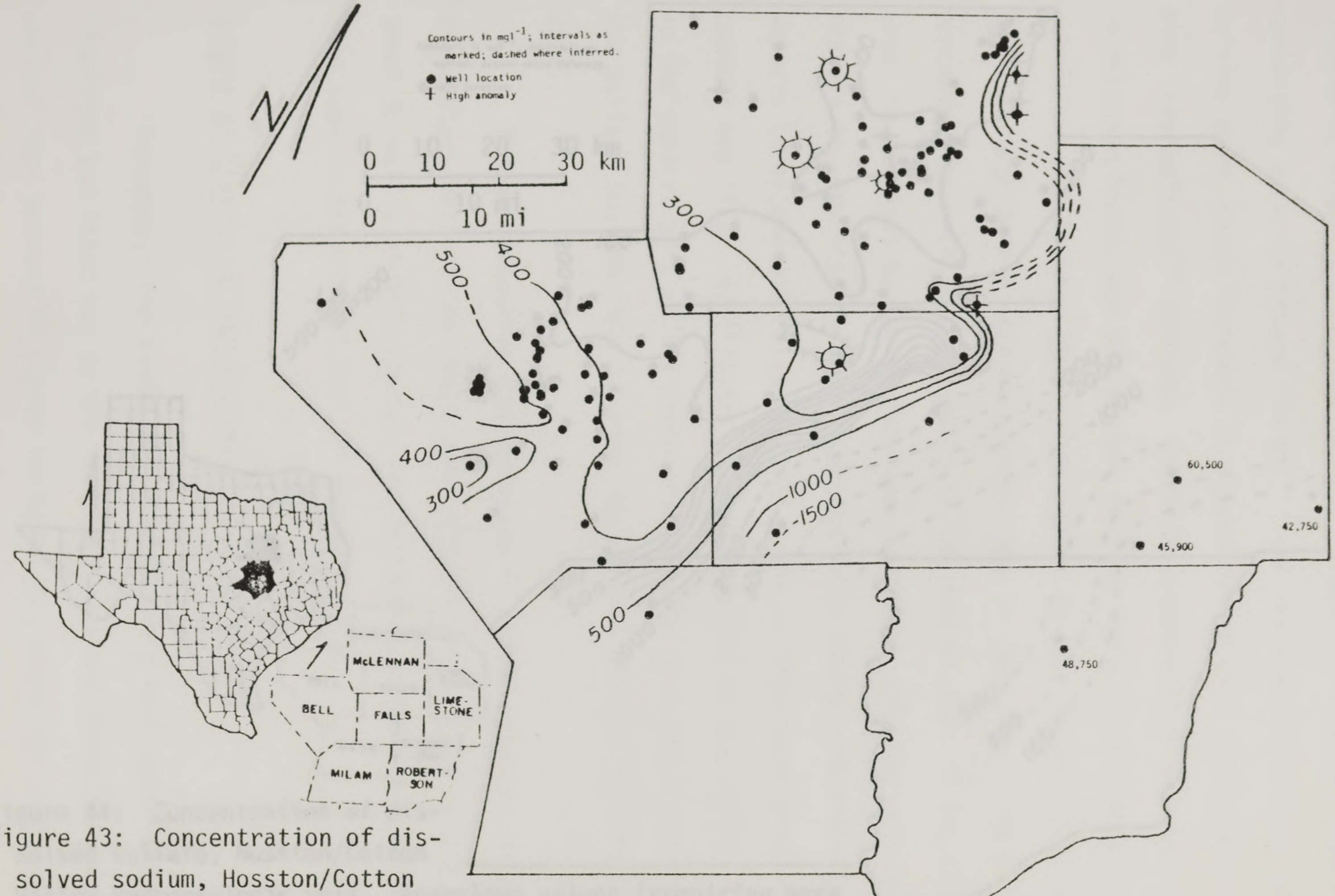


Figure 43: Concentration of dissolved sodium, Hosston/Cotton Valley hydrogeologic unit. Actual values are printed next to sample locations in the eastern half of the study area. The transition zone between meteoric and basinal waters is shown by the abrupt increase in sodium concentration in the central region.

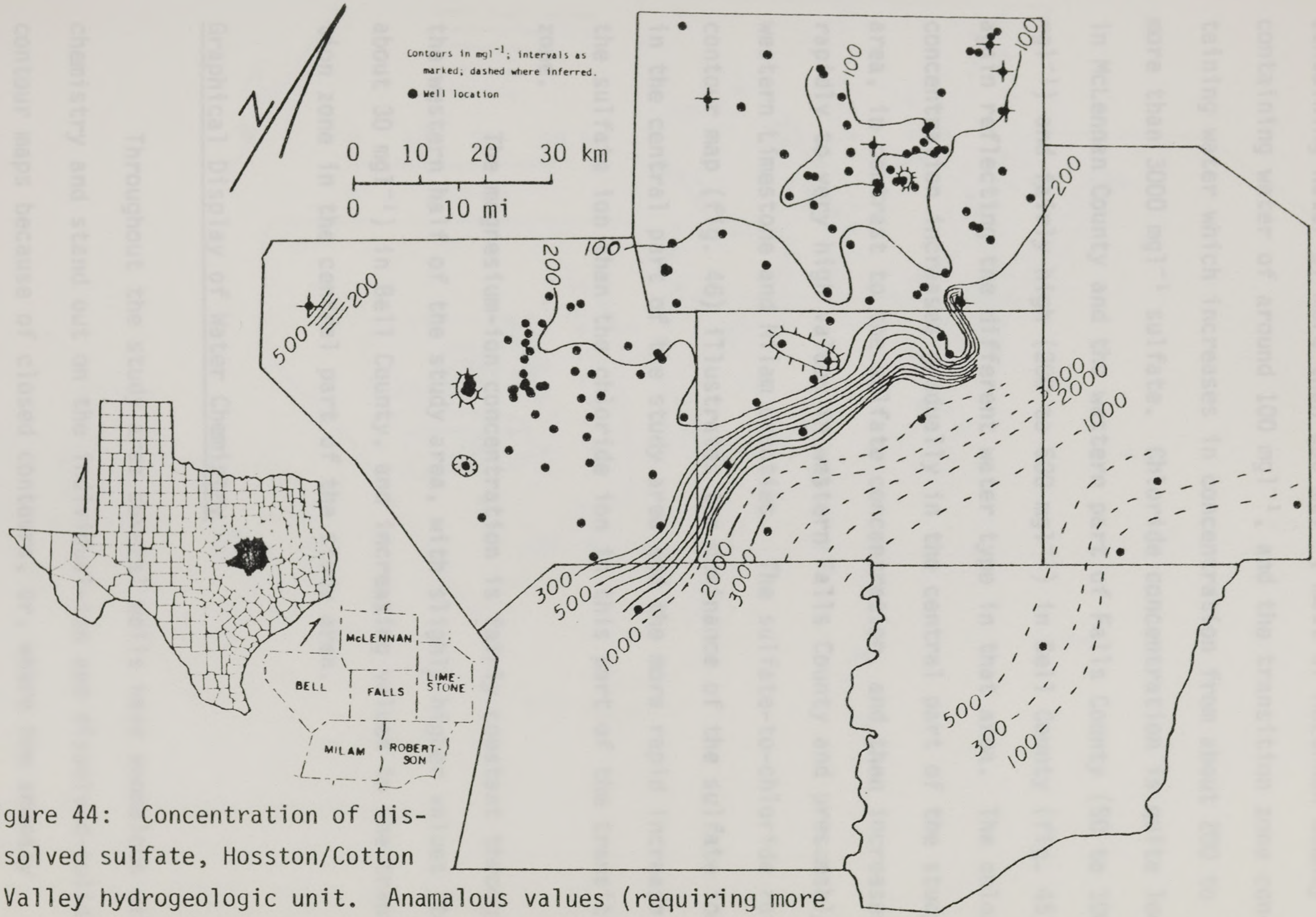


Figure 44: Concentration of dissolved sulfate, Hosston/Cotton Valley hydrogeologic unit. Anamalous values (requiring more than one close contour) are shown by "+". The very high sulfate concentration in the central part of the study area may be due to oxidation of H_2S moving out of the basin.

containing water of more than 200 mgl^{-1}, most of McLennan County containing water of around 100 mgl^{-1}, and the transition zone containing water which increases in concentration from about 200 to more than 3000 mgl^{-1} sulfate. Chloride concentration is quite low in McLennan County and the western part of Falls County (50 to 100 mgl^{-1}) and fairly high (200 to 500 mgl^{-1}) in Bell County (fig. 45), again reflecting the different water type in that area. The chloride concentration increases gradually in the central part of the study area, in contrast to the sulfate concentration, and then increases rapidly to very high values in western Falls County and presumably western Limestone and Milam Counties. The sulfate-to-chloride ratio contour map (fig. 46) illustrates the dominance of the sulfate ion in the central part of the study area and the more rapid increase in the sulfate ion than the chloride ion in this part of the transition zone.

The magnesium-ion concentration is fairly constant throughout the western half of the study area, with slighly higher values (to about 30 mgl^{-1}) in Bell County, and increasing values in the transition zone in the central part of the study area.

Graphical Display of Water Chemistry

Throughout the study area several wells have anomalous water chemistry and stand out on the individual-ion and dissolved-solids contour maps because of closed contours, or, where the anomaly warranted more than one closed contour, by a "+" symbol. Representative

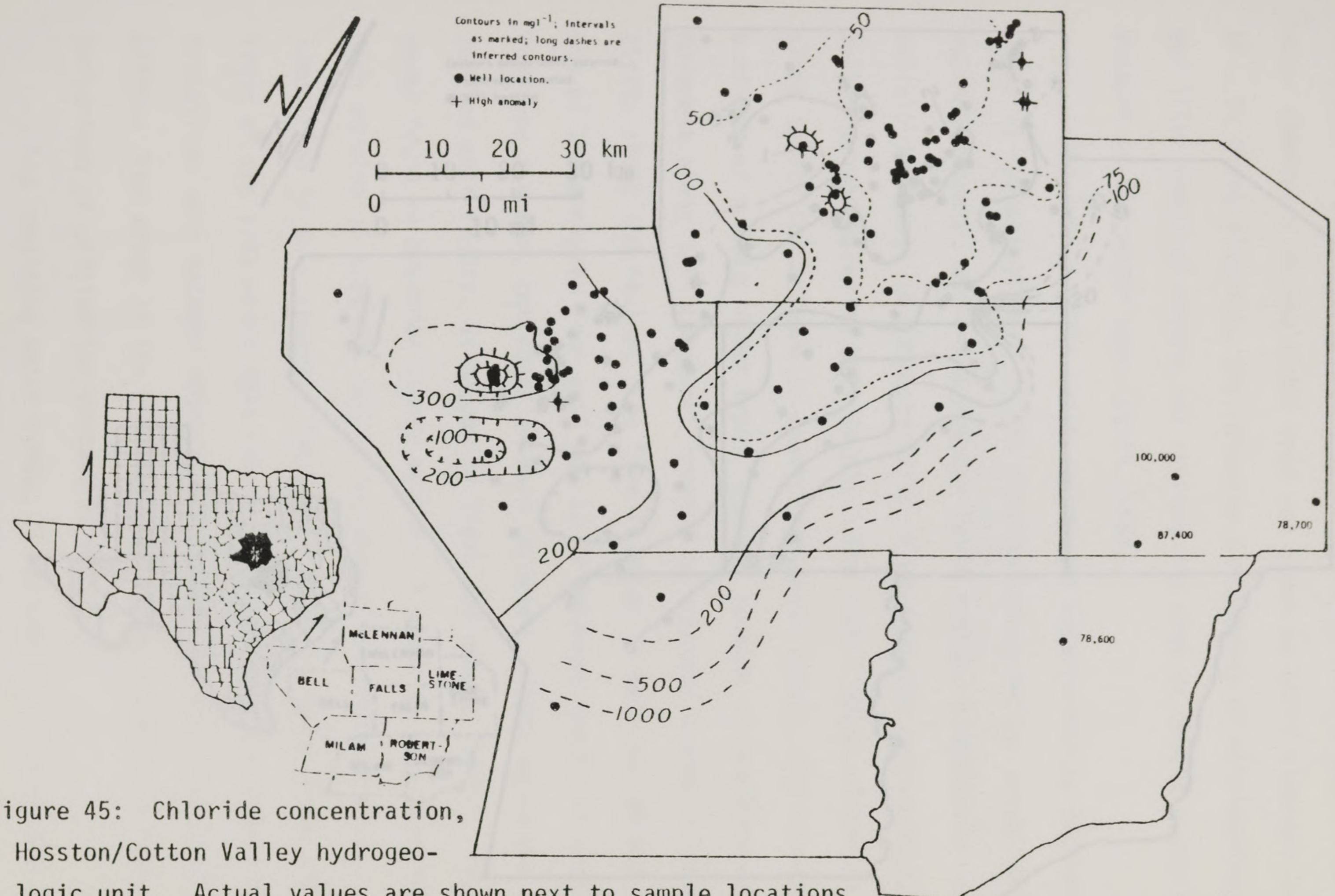


Figure 45: Chloride concentration, Hosston/Cotton Valley hydrogeologic unit. Actual values are shown next to sample locations in the eastern half of the study area. The central part of the study area is not a zone of simple mixing of basinal (Na-Cl) water with meteoric water because the chloride concentration does not increase along with the sodium.

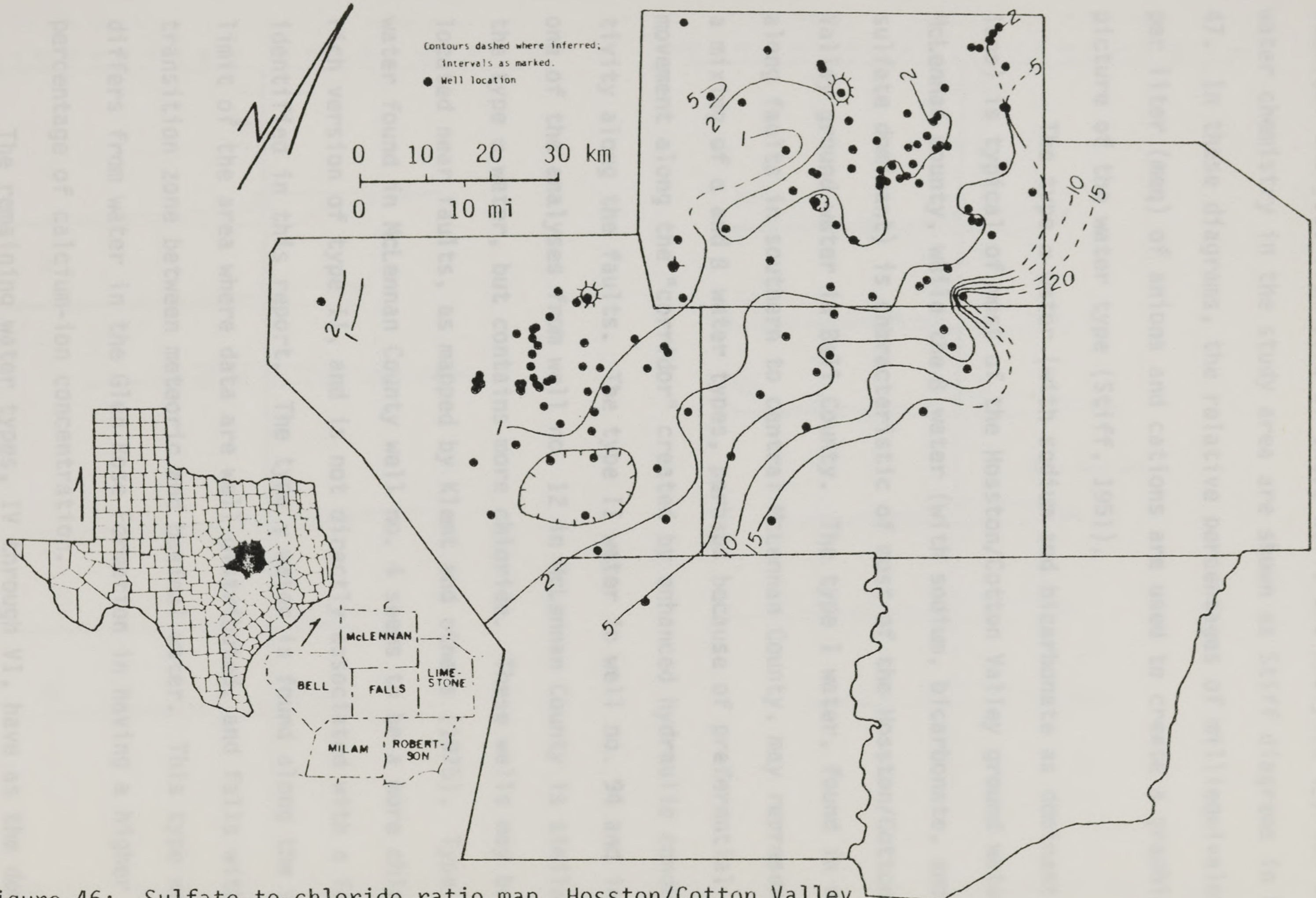


Figure 46: Sulfate-to-chloride ratio map, Hosston/Cotton Valley hydrogeologic unit. Although not shown, ratios in the eastern half of the study area are very small (much less than one).

chemical analyses from some of these wells and analyses typical of the water chemistry in the study area are shown as Stiff diagrams in Figure 47. In these diagrams, the relative percentages of milliequivalents per liter (meq) of anions and cations are used to create a graphical picture of the water type (Stiff, 1951).

The type α water (with sodium and bicarbonate as dominant ions) is typical of most of the Hosston/Cotton Valley ground water in McLennan County, while the β water (with sodium, bicarbonate, and sulfate dominant) is characteristic of most of the Hosston/Cotton Valley ground water in Bell County. The type I water, found in wells along faults in southern to central McLennan County, may represent a mixing of α and β water types, perhaps because of preferential movement along the "corridor" created by enhanced hydraulic conductivity along the faults. The type II water in well no. 94 and in one of the analyses from well no. 12 in McLennan County is similar to the type α water, but contains more chloride. These wells may be located near faults, as mapped by Klemt and others (1975). Type III water found in McLennan County well no. 4 seems to be a more chloride-rich version of type II, and is not directly associated with a fault identified in this report. The type γ water is found along the eastern limit of the area where data are well distributed, and falls within the transition zone between meteoric and basinal water. This type water differs from water in the Glen Rose Formation in having a higher percentage of calcium-ion concentration.

The remaining water types, IV through VI, have as the dominant anions bicarbonate and sulfate, chloride and sulfate, or sulfate. These

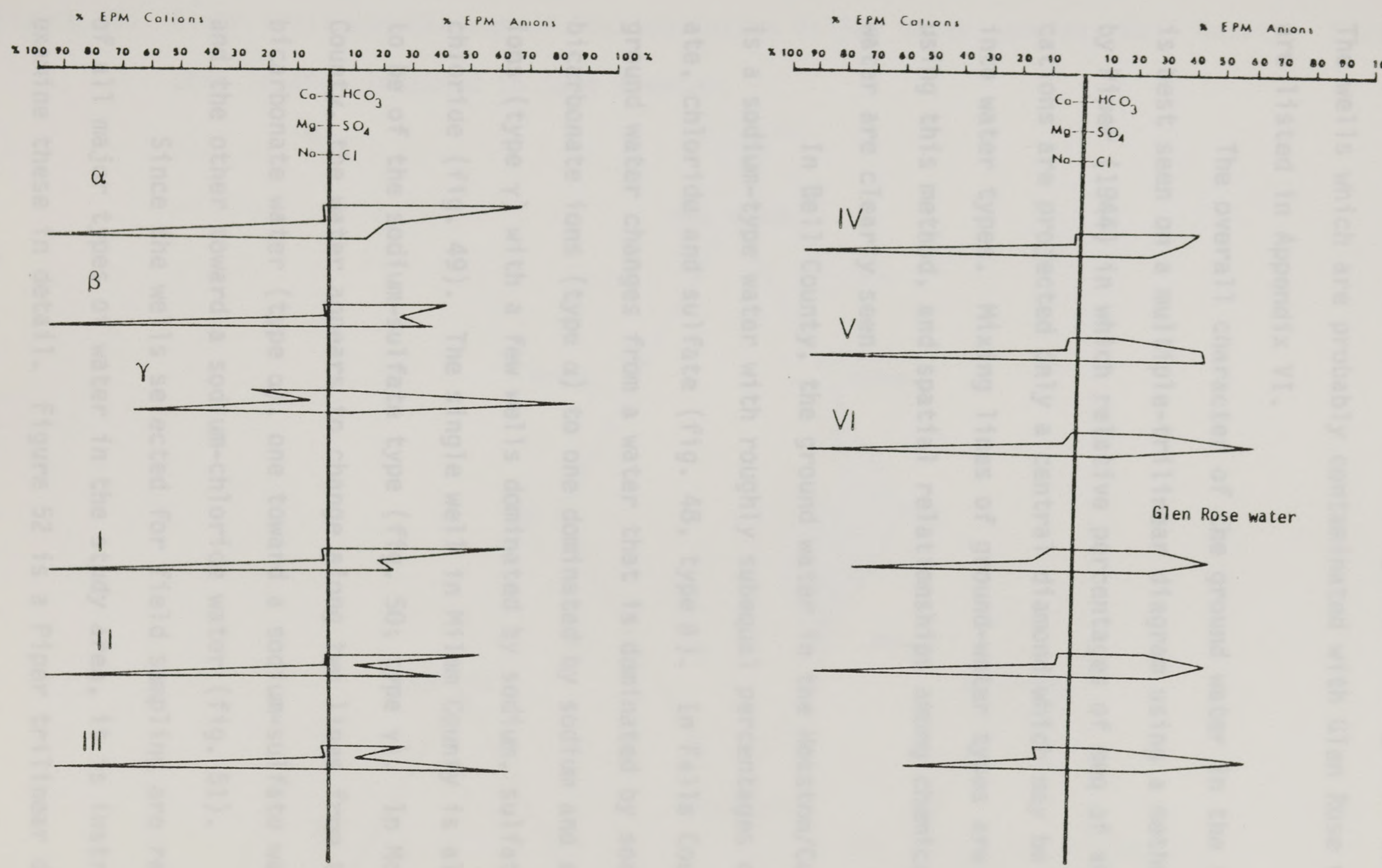


Figure 47: Graphical representations of water-chemistry types in the Falls County study area.

are reminiscent of Glen Rose water and probably represent downward leakage of Glen Rose water along well casings or faults. The wells which are probably contaminated with Glen Rose water are listed in Appendix VI.

The overall character of the ground water in the study area is best seen on a multiple-trilinear diagram using a method developed by Piper (1944) in which relative percentages of meq of anions and cations are projected only a central diamond which may be divided into water types. Mixing lines of ground-water types are evident using this method, and spatial relationships among chemical types of water are clearly seen.

In Bell County, the ground water in the Hosston/Cotton Valley is a sodium-type water with roughly subequal percentages of bicarbonate, chloride and sulfate (fig. 48, type β). In Falls County, the ground water changes from a water that is dominated by sodium and bicarbonate ions (type α) to one dominated by sodium and sulfate ions (type γ) with a few wells dominated by sodium, sulfate and chloride (fig. 49). The single well in Milam County is also shown to be of the sodium-sulfate type (fig. 50; type γ). In McLennan County, the water appears to change along two lines from the sodium-bicarbonate water (type α), one toward a sodium-sulfate water (type γ) and the other toward a sodium-chloride water (fig. 51).

Since the wells selected for field sampling are representative of all major types of water in the study area, it is instructive to examine these in detail. Figure 52 is a Piper trilinear diagram of these samples; the mixing lines of the ground waters are more

Figure 48: Piper trilinear diagram of Hosston/Cotton Valley water samples, Bell County. Striped area is area included in type β water.

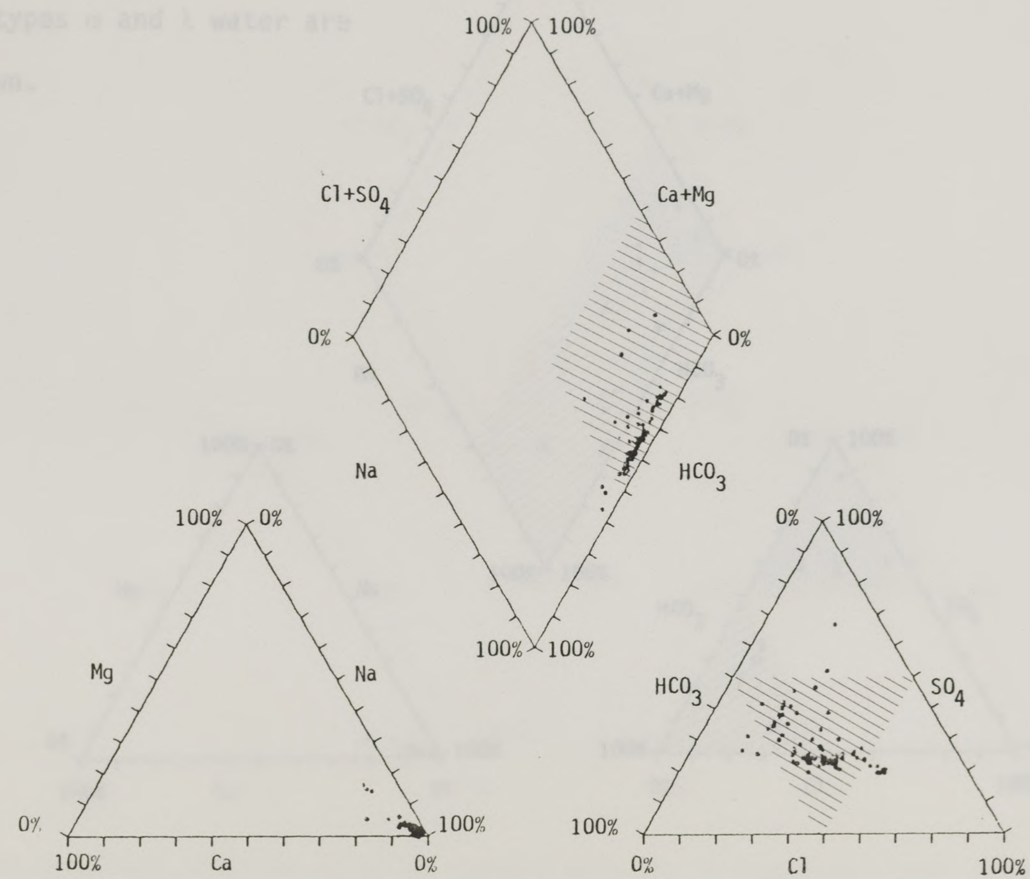
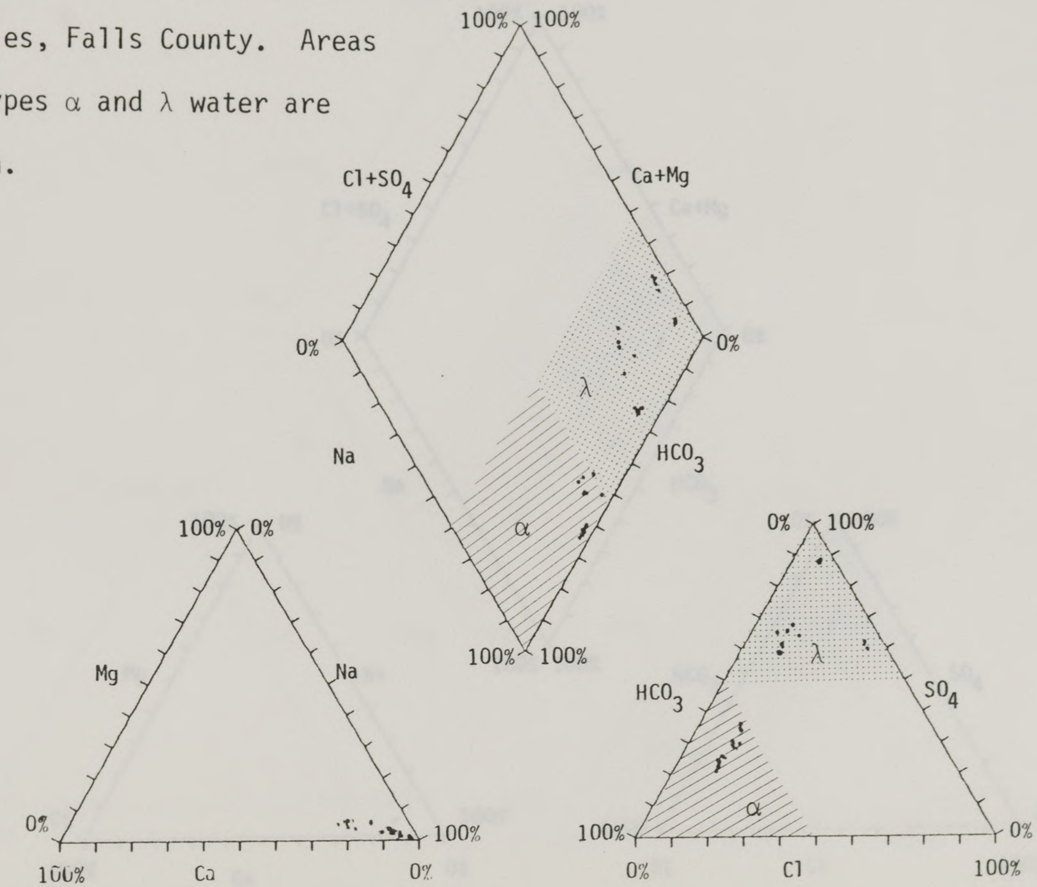


Figure 49: Piper trilinear diagram of Hosston/Cotton Valley water samples, Falls County. Areas of types α and λ water are shown.



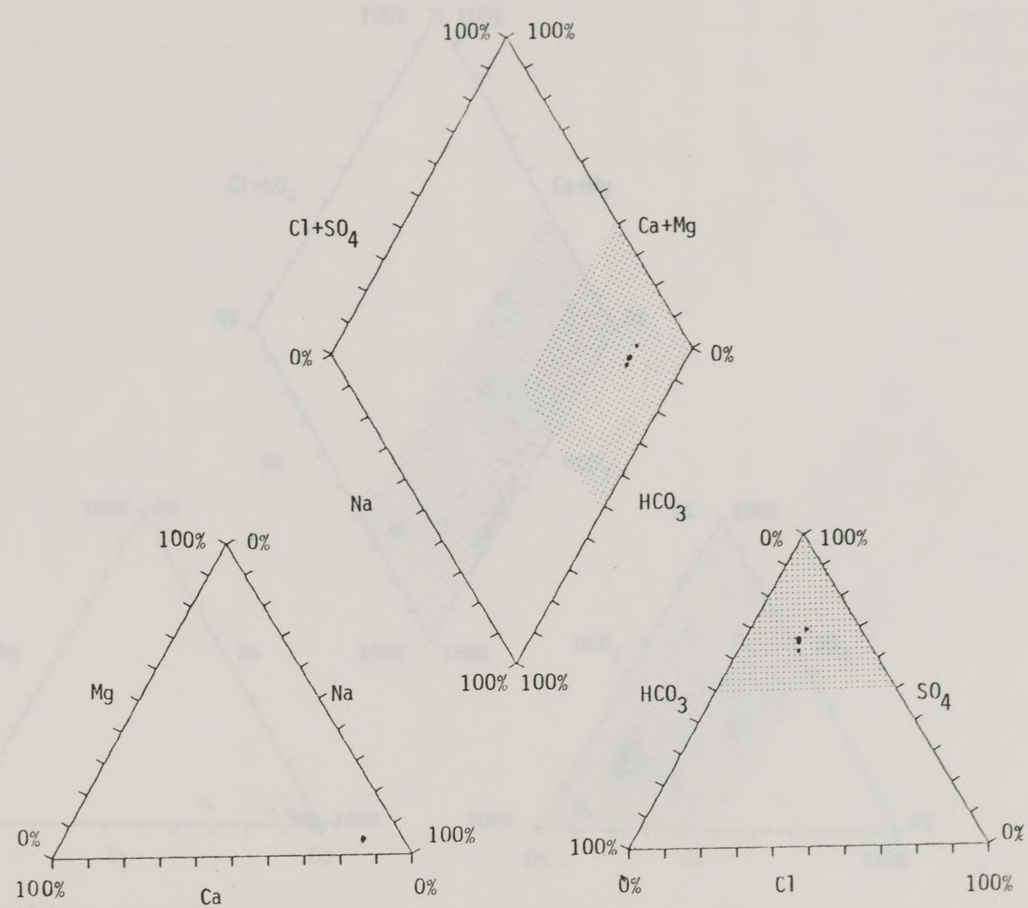


Figure 50: Piper trilinear diagram of Milam County well no. 1 (analyses from several years). The samples fall in the type λ field, shown as the stippled pattern.

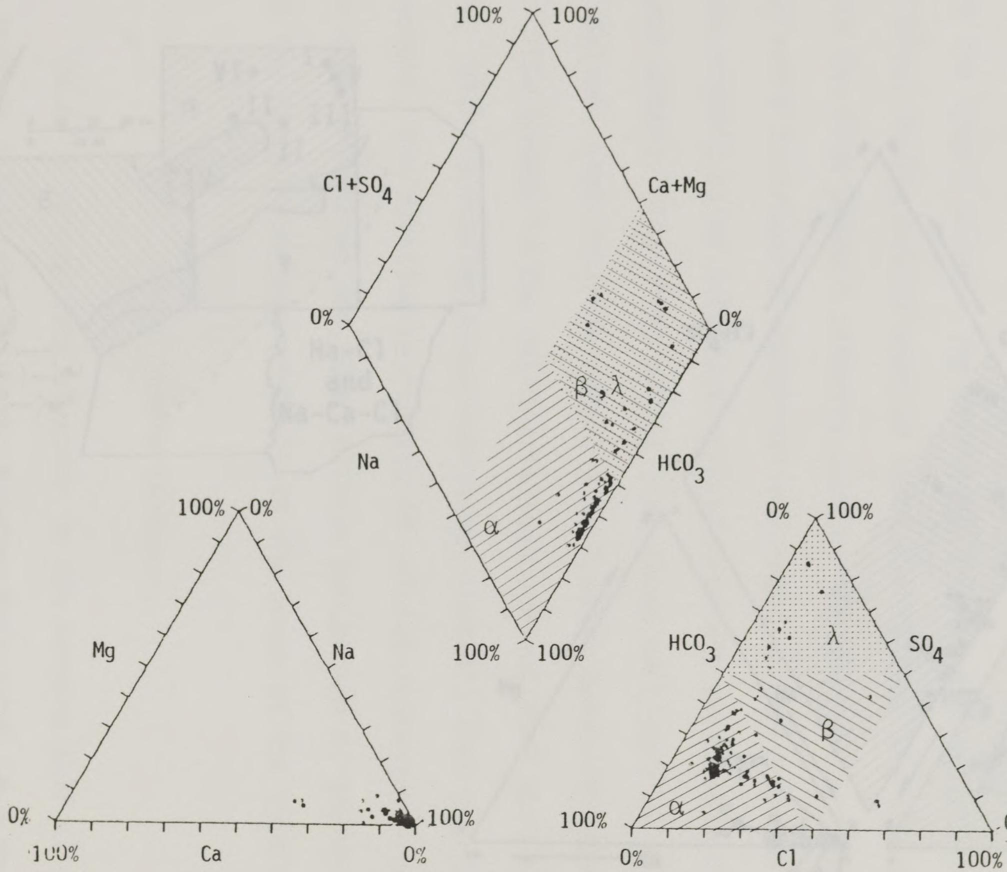


Figure 51: Piper trilinear diagram of Hosston/Cotton Valley water samples, McLennan County. Samples fall into type α, β, and λ waters, as shown by patterns.

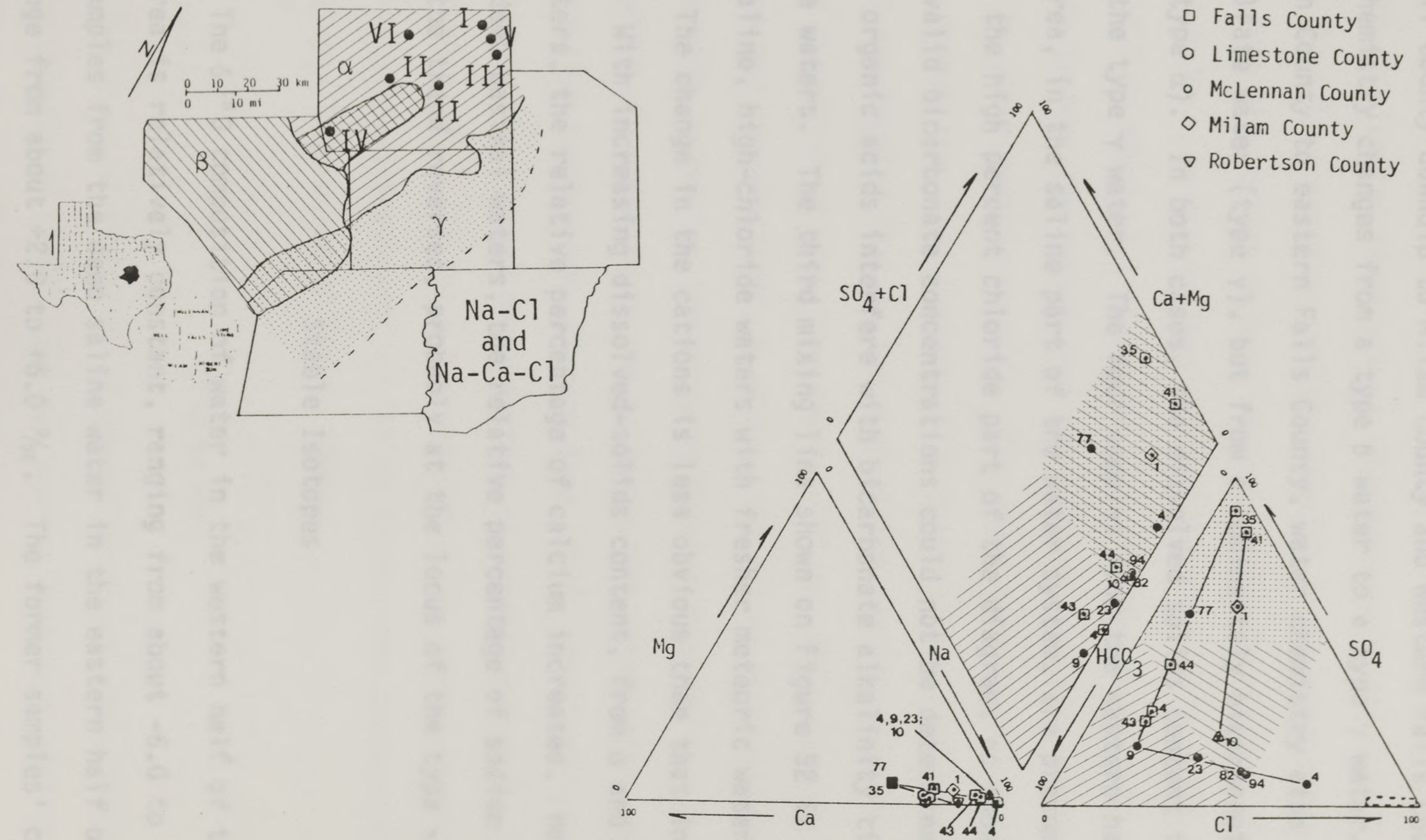


Figure 52: Piper trilinear diagram of water chemistry from samples collected during this investigation and from Falls County well no. 35. Diagram on the left shows the spatial relationships of the different water chemistry types in the Hosston/Cotton Valley in the study area.

apparent. The mixing lines of the anions are particularly striking. From Bell County downdip to Milam County and western Falls County, water chemistry changes from a type β water to a type γ water. From McLennan County to eastern Falls County, water chemistry also changes to a sulfate water (type γ), but from a dominantely bicarbonate water (type α). In both cases, the dissolved solids content increases toward the type γ water. The four samples from the eastern half of the study area, in the saline part of the water system, are presumed to fall in the high percent chloride part of the diagram, as shown, although valid bicarbonate concentrations could not be determined because organic acids interfere with bicarbonate alkalinity titrations in these waters. The third mixing line shown on Figure 52 is that of these saline, high-chloride waters with fresher meteoric waters.

The change in the cations is less obvious than that in the anions. With increasing dissolved-solids content, from α and β waters to γ waters, the relative percentage of calcium increases. However, in the deep basinal waters, the relative percentage of sodium is high, and so the trend reverses, probably at the locus of the type γ waters.

Stable Isotopes

The $\delta^{18}O$ composition of water in the western half of the study area is relatively constant, ranging from about -6.0 to -5.3 ‰, while samples from the deep saline water in the eastern half of the area range from about +2.0 to +6.0 ‰. The former samples' composition indicates a meteoric-water origin for the ground water, as expected. The latter samples' composition, relatively enriched in ^{18}O, is probably the result of isotopic exchange with the hosting formation at elevated temperatures (Prezbendowski, 1981).

The $\delta^{13}C$ composition of the samples is somewhat more variable. Samples from the western half of the area range from about -11.7 to about -8.0 ‰. In the eastern half of the area, $\delta^{13}C$ ranges from about -17.5 to about -2.1 ‰. The $\delta^{13}C$ measured represents the carbonate system; the method does not measure isotopic composition of methane or other organic carbons. The water samples with a sodium-sulfate composition have depleted $\delta^{13}C$ compositions (-10 to about -12 ‰) approaching that of the deep saline samples (-12 to -18 ‰, with the exception of Limestone County well no. 93). According to Carothers and Kharaka (1980, p. 330), $\delta^{13}C$ values of bicarbonate decrease with increasing temperatures greater than 100°C. The two values which are depleted in the saline water regions also probably have formation temperatures of more than 100°C. This depletion is attributed to the thermal decomposition of organic matter to CO_2 and hydrocarbon gases. All the wells sampled in the eastern half of the study area are gas-producers; no fields in the area produce oil (The Railroad Commission of Texas, 1980).

Discussion

The chemical evolution of ground water was first discussed in detail by Chebotarev (1955), and has been an important tool in most types of hydrologic studies ever since. The typical evolution of meteoric ground water from that of a calcium-bicarbonate type to a sodium-bicarbonate type has been explained as the result of cation exchange on clays and dissolution of carbonates by soil CO_2 or CO_2 from organic matter in the aquifer (Kreitler and others, 1981). The composition of deep saline brines, becoming more calcium-rich relative to sodium in the shallower parts of the Edwards Aquifer in South Texas, has been explained by various processes, including that of dedolimitization and albitization (Prezbendowski, 1981; Land and Prezbendowski, 1982). The generation of sodium-sulfate ground water, on the other hand, has not been extensively studied. Rightmire and others (1976) have studied sulfate waters in the Edwards Formation in South Texas and concluded that the sulfate in these waters is the result of oxidation of H_2S from a downdip source. Others have suggested that the high sulfate in ground water is the result of dissolution of gypsum or anhydrite (Freeze and Cherry, 1979, p. 243).

One way to account for the changes in water chemistry is to write a series of chemical reactions which may have controlled mineral precipitation and dissolution. Table III shows three possible ways to account for the changes along the mixing line from Bell County no. 10 to Falls County no. 41 (fig. 52). This alteration of water chemistry from a type β water to a type γ water is not significantly different from a change from a type α water to a type γ water, so only the former is shown. Although the reactions are written as a change from one type of water to another, no direction is implied; the change could easily be in the opposite direction.

TABLE III: Chemical reactions which may account for changes in water chemistry in the Hosston/Cotton Valley hydrogeologic unit, Falls County study area.

Table IIIA: Alteration of feldspar to kaolinite.

REACTION[1]	Ca[2]	Mg[2]	Na[2]	K[2]	HCO_3[2]	SO_4[2]	Cl[2]	H_4SiO_4[2]	CO_2[2]	H_2S[2]	O_2[2]
1) Initial concentration	5.29	1.31	42.34	0.43	2.42	26.42	0.71	0.048			
2) Subtract Na-Cl brine	5.24	1.30	41.66	0.42	2.32	26.42	0.0	0.048			
3) Change kaolinite back to potassium feldspar	5.24	1.30	41.66	0.00	1.90	26.42	0.00	-0.79	0.42		
4) Reduce sulfate to hydrogen sulfide	5.24	1.30	41.66	0.00	54.77	0.00	0.00	-0.79	-52.42	26.42	52.84
5) Change kaolinite back to albite	5.24	1.30	0.00	0.00	13.08	0.00	0.00	-84.11	-10.76	26.42	52.84
6) Precipitate dolomite	3.94	0.00	0.00	0.00	7.88	0.00	0.00	-84.11	-8.16	26.42	52.84
7) Precipitate calcite	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-84.11	-12.1	26.42	52.84

[1] Full balanced reaction shown below.

[2] Concentration of dissolved species or gas in mmol.

1) Initial concentration is calculated from the difference between chemical analyses from Falls County no. 41 (type γ water) and Bell County no. 10 (type β water). Bicarbonate concentration is adjusted to balance electrical charge.
2) The sodium-chloride brine is based on Robertson Co. no. 25 water analysis.
3) $0.21Al_2Si_2O_5(OH)_4 + 0.42K^+ + 0.84H_4SiO_4 + 0.42HCO_3^- \rightarrow 0.42KAlSi_3O_8 + 2.31H_2O + 0.42CO_2$
4) $26.42SO_4^{-2} + 52.84CO_2 + 52.84H_2O \rightarrow 26.42H_2S + 52.84CO_2 + 52.84HCO_3^-$
5) $20.83Al_2Si_2O_5(OH)_4 + 41.66Na^+ + 83.32H_4SiO_4 + 41.66HCO_3^- \rightarrow 41.66NaAlSi_3O_8 + 229.13H_2O + 41.66CO_2$
6) $1.30Ca^{+2} + 1.30Mg^{+2} + 5.2HCO_3^- \rightarrow 1.30CaMg(CO_3)_2 + 2.6H_2O + 2.6CO_2$
7) $3.94Ca^{+2} + 7.88HCO_3^- \rightarrow 3.94CaCO_3 + 3.94H_2O + 3.94CO_2$

Table IIIB: Dissolution of calcite and cation exchange on clays.

REACTION[1]	Ca^2	Mg^2	Na^2	K^2	HCO_3[2]	SO_4[2]	Cl[2]	H_4SiO_4[2]	CO_2[2]	H_2S[2]	O_2[2]
1) Initial concentration	5.29	1.31	42.34	0.43	2.42	26.42	0.71	0.048			
2) Subtract Na-Cl brine	5.24	1.30	41.66	0.42	2.32	26.42	0.00	0.048			
3) Change kaolinite back to potassium feldspar	5.24	1.30	41.66	0.00	1.90	26.42	0.00	-0.79	0.42		
4) Reduce sulfate to hydrogen sulfide	5.24	1.30	41.66	0.00	54.77	0.00	0.00	-0.79	-52.42	26.42	52.84
5) Precipitate dolomite	3.94	0.00	41.66	0.00	49.47	0.00	0.00	-0.79	-49.82	26.42	52.84
6) Exchange Ca^{+2} for Na^+ on clay	24.77	0.00	0.00	0.00	49.57	0.00	0.00	-0.79	-49.82	26.42	52.84
7) Precipitate calcite	0.00	0.00	0.00	0.00	0.03	0.00	0.00	-0.79	-25.05	26.42	52.84

[1]Complete balanced reactions shown below.

[2]Concentration of dissolved species or gas in mmol.

1) Initial concentration is calculated from the difference between chemical analyses from Falls County no. 41 (type γ water) and Bell County no. 10 (type β water). Bicarbonate concentration is adjusted to balance electrical charge.
2) The sodium-chloride brine is based on Robertson Co. no. 25 water analysis.
3) $0.21\ Al_2Si_2O_5(OH)_4 + 0.42K^+ + 0.84H_4SiO_4 + 0.42HCO_3^- \rightarrow 0.42KAlSi_3O_8 + 2.31H_2O + 0.42CO_2$
4) $26.42SO_4^{-2} + 52.84CO_2 + 52.84H_2O \rightarrow 26.42H_2S + 52.84O_2 + 52.84HCO_3^-$
5) $1.30Ca^{+2} + 1.30Mg^{+2} + 5.2HCO_3^- \rightarrow 1.30CaMg(CO_3)_2 + 2.6H_2O + 2.6CO_2$
6) $41.66Na^+ + 20.83$Ca-montmorillonite $\rightarrow 20.83Ca^{+2} + 20.83Na_2$-montmorillonite
7) $24.77Ca^{+2} + 49.54HCO_3^- \rightarrow 24.77CaCO_3 + 24.77H_2O + 24.77CO_2$

Table IIIC: Alteration of feldspar to illite.

REACTION[1]	Ca[2]	Mg[2]	Na[2]	K[2]	HCO_3[2]	SO_4[2]	Cl[2]	H_4SiO_4[2]	CO_2[2]	H_2S[2]	O_2[2]
1) Initial concentration	5.29	1.31	42.34	0.43	2.42	26.42	0.71	0.048			
2) Subtract Na-Cl brine	5.24	1.30	41.66	0.42	2.32	26.42	0.0	0.048			
3) Precipitate dolomite	3.94	0.0	41.66	0.42	-2.88	26.42	0.0	0.048	2.6		
4) Change illite back to albite	3.94	0.0	0.0	8.752	-36.208	26.42	0.0	-66.608	35.928		
5) Reduce sulfate to hydrogen sulfide	3.94	0.0	0.0	8.752	16.632	0.0	0.0	-66.608	-16.912	26.42	52.84
6) Change illite back to potassium feldspar	3.94	0.0	0.0	-8.332	-0.452	0.0	0.0	-100.776	0.172	26.42	52.84
7) Change illite back to anorthite	-16.89	0.0	0.0	0.0	-33.78	0.0	0.0	-84.112	33.5	26.42	52.84
8) Dissolve calcite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-84.112	16.61	26.42	52.84

[1]Complete balanced reactions shown below.

[2]Concentration of dissolved species or gas in mmol.

1) Initial concentration is calculated from the difference between chemical analyses from Falls County no. 41 (type γ water) and Bell County no. 10 (type β water). Bicarbonate concentration is adjusted to balance electrical charge.
2) The sodium-chloride brine is based on Robertson Co. no. 25 water analysis.
3) $1.30Ca^{+2} + 1.30Mg^{+2} + 5.2HCO_3^- \rightarrow 1.30CaMg(CO_3)_2 + 2.6H_2O + 2.6CO_2$
4) $16.664K_{0.5}Al_{2.5}Si_{3.5}O_{10}(OH)_2 + 66.656H_4SiO_4 + 41.66Na^+ + 33.328HCO_3^- \rightarrow 41.66NaAlSi_3O_8 + 8.332K^+ + 33.328CO_2 + 166.64H_2O$
5) $26.42SO_4^{-2} + 52.84CO_2 + 52.84H_2O \rightarrow 26.42H_2S + 52.84O_2 + 52.84HCO_3^-$
6) $8.542K_{0.5}Al_{2.5}Si_{3.5}O_{10}(OH)_2 + 17.084K^+ + 34.168H_4SiO_4 + 17.084HCO_3^- \rightarrow 21.355KAlSi_3O_8 + 17.084CO_2 + 85.42H_2O$
7) $16.664K_{0.5}Al_{2.5}Si_{3.5}O_{10}(OH)_2 + 20.83Ca^{+2} + 33.328HCO_3^- \rightarrow 20.83CaAl_2Si_2O_8 + 8.332K^+ + 33.328CO_2 + 16.664H_4SiO_4$
8) $16.89CaCO_3 + 16.89CO_2 + 16.89H_2O \rightarrow 16.89Ca^{+2} + 33.78HCO_3^-$

The difference between the β and γ waters does not result from a simple mixing of basinal water with meteoric water, because the chloride concentration does not increase in concert with sodium, and the sulfate concentrations are much higher than those found in basinal waters. The increase in sulfate must be the result of oxidation of H_2S because there is little or no gypsum or anhydrite in the Hosston/Cotton Valley in the study area. One sample (Falls County no. 32), in the eastern part of the study area where natural gas production is occurring, contained a measureable abount of H_2S. However, none of the other samples which were tested contained detectable amounts of this gas.

The source of the sodium and perhaps the calcium is problematical. As shown in Table III, there are at least two sources for the sodium. One source is that of alteration of plagioclase to kaolinite or illite. The second is dissolution of calcite with subsequent exchange of calcium for sodium on clays. The only core from the sodium-sulfate zone is a single 15-cm long piece from the T.H.S. Memorial Hospital geothermal well (Falls County no. 35). There are no unaltered feldspars in this core, which is a coarse-grained sandstone with some granule-size quartz and chert grains, and only a suggestion of altered feldspars. The only clay present in this core is a very small amount of illite. Furthermore, there is only a small amount of calcite present.

The remaining consequences of the chemical reactions in Table III are more easily documented. Quartz overgrowths are plentiful in the core, and the chemical reactions in Table III predict release of silicic acid (H_4SiO_4) which, if saturation is reached, could result in precipitation of silica. The change in pH between Bell County no. 10 (pH of 8.5) and Falls County no. 41 (pH of 7.3) could result from the release of carbon dioxide, as predicted in Table IIIA and IIIB. A small amount of dolomite is needed to account for changes in magnesium concentration, and alteration of a small amount of potassium feldspar to kaolinite or illite is also required. Both of these reactions are a very minor part of the total system, and although the reactions affecting them are reasonable, the magnesium and potassium might also result from alteration of impure plagioclase.

Because of the dearth of sediment samples, and, in particular, core, it is impossible to conclude which of the possible sets of chemical reactions is the most appropriate to the Hosston/Cotton Valley aquifer. Further examination of the origin of the water chemistry must involve extensive study of the diagenesis of the rocks, when samples become available.

SUMMARY AND DISCUSSION

As shown in Table IV, the geothermal gradient of any aquifer can be affected by a variety of factors. In the Hosston/Cotton Valley hydrogeologic unit, the geothermal gradient may be affected by those factors which are highlighted. These are discussed below.

In the western part of the study area, lateral changes in the thermal conductivity of the underlying basement rocks may affect the geothermal gradient. Flawn and others (1963), using limited data, have mapped regional facies changes in the Ouachita basement rocks in the study area, but only general trends can be discerned. Thrust faults and facies changes parallel the strike of the Hosston/Cotton Valley, and also parallel the strike of areas of high geothermal gradient. Although no heat flow studies have been attempted in this area, it is unlikely that heat flow is variable; there is no evidence of either ancient or recent pluton emplacement in the Ouachita rocks in the study area. The wide range of geothermal gradients found at depths of less than one km suggests that either thermal conductivity is affecting the gradients or that ground-water recharge is locally depressing isotherms in the aquifer and creating an apparent low geothermal gradient. Because there is little correlation between water temperature (fig. 29) and net-sand or total thickness of the aquifer, which is where maximum recharge should be occurring, it seems unlikely that recharging ground water is affecting the geothermal gradient. Furthermore, the

TABLE IV: Summary of factors affecting geothermal gradient in the Falls County study area (→).

	INPUT	GEOTHERMAL GRADIENT	REQUIREMENTS
	Geothermics		
	Variable heat flow, Q_h	Variable G	Source for heat
→	Variable thermal conductivity, K_h, in underlying rocks	Variable G	Lateral change in K_h in underlying rocks
	Hydrology		
	Updip flow of hot, basinal ground water	High G in mixing zone	Hydraulic head higher in deep basin than updip; mixing of high dissolved-solids Na-Cl water with low dissolved-solids $Na\text{-}HCO_3$ water
→	Updip flow of gases from the basin	?	If H_2S, then either presence of H_2S or SO_4^{-2} in the mixing zone
→	Upward flow along faults	High G along faults	Hydraulic head lower near faults than in surrounding region; presence of large volumes of Na-Cl water near faults
		No change in G	Hydraulic head lower near faults; presence of some wells with anomalous Na-Cl water chemistry

distance to the outcrop area of the Hosston, where recharge is occurring, is far enough (8 to 80 km) that ground water entering the study area from upgradient sources should be at equilibrium with surrounding sediments. Furthermore, there is no correlation between low geothermal gradients and that part of the study area which is closest to the outcrop of the Hosston Sand. Finally, the thickness of the aquifer, the distance to the recharge area, and the hydraulic gradient contribute to the conclusion that the dominant heat-flow mechanism in the western part of the study area is conduction (see Table II).

The chemical composition of the water in the western part of the aquifer suggests that some wells are being affected by high dissolved-solids ground water, resulting in Na-Cl type water chemistry. These wells are always associated with faults in the Balcones Fault Zone; a cursory examination of water chemistry of shallower aquifers in the study area revealed no obvious source for this water. The volume of Na-Cl brine being discharged into the Hosston/Cotton Valley is small and does not affect water temperature and so is not important to the geothermal regime, but the conclusion that these wells are being affected by brines discharging from the underlying Ouachita rocks is somewhat problematical and unsatisfactory.

In the eastern part of the study area, the Hosston/Cotton Valley is more than ten times as thick as in the western part of the study area and geothermal gradients are relatively constant at less than 30°C/km. Furthermore, there is little variation in geothermal gradient with depth, and formations above and below the Hosston/Cotton

Valley appear to have comparable geothermal gradients. High geothermal-gradient anomalies occur along the Mexia Fault Zone and hydraulic heads along the Mexia Fault Zone are lower than in the surrounding region, suggesting that faults are loci for upward discharge of basinal water. Hydraulic heads in the Glen Rose and Smackover Formations (above and below the Hosston/Cotton Valley) are lower and higher, respectively, than heads in the Hosston/Cotton Valley, providing the potential for upward movement of basinal waters. Scarcity of water chemistry data in the eastern part of the Hosston/Cotton Valley prohibits an examination of chemical variations in the aquifer near the geothermal anomalies. The thickness of the aquifer in this region along with the hydraulic head and physical properties of the aquifer suggest that the dominant heat-flow mechanism in this area is convection (see Table II). Ground-water flux may be small in this part of the aquifer, but may be affecting geothermal gradient distribution.

In the central part of the study area, geothermal gradients are high (greater than 40°C/km) and the water chemistry suggests a mixing of H_2S from the basin with meteoric ground water. The relatively constant chloride concentration in this transition zone is evidence that the basinal gases (H_2S) are moving independently of basinal waters (Na-Cl brines), and therefore two-phase flow must be occurring. Without better hydraulic-head data, it is difficult to describe adequately the interaction between meteoric and basinal gases or water and their influence on geothermal gradient. The dominant heat-transfer mechanism, however, is probably forced convection (that is, convection affected by ground-water flow; see Table II and fig. 53 for summary).

Use of the Hosston/Cotton Valley as a Low-Temperature Geothermal Resource

The relatively high geothermal gradients in the study area and the relatively high water temperatures favor the use of the Hosston/Cotton Valley as a low-temperature ground-water resource. Transmissivity in the Hosston/Cotton Valley is adequate throughout the western and central parts of the study area for production of ground water. Most of central McLennan County and most of the central part of the study area (see fig. 39) have high geothermal gradients and are optimum areas for low-temperature geothermal ground water (fig. 53). In McLennan County water quality is good (dissolved solids less than 1000 mgl^{-1}) and multiple use of the water could be made. In the central part of the study area where water quality is poor and temperatures are high, multiple use of the water is not possible. The declining water level in the western and central parts of the study area is a serious problem; any production of the Hosston/Cotton Valley ground water for use as a heat source should include a program for reinjection of the water into the aquifer.

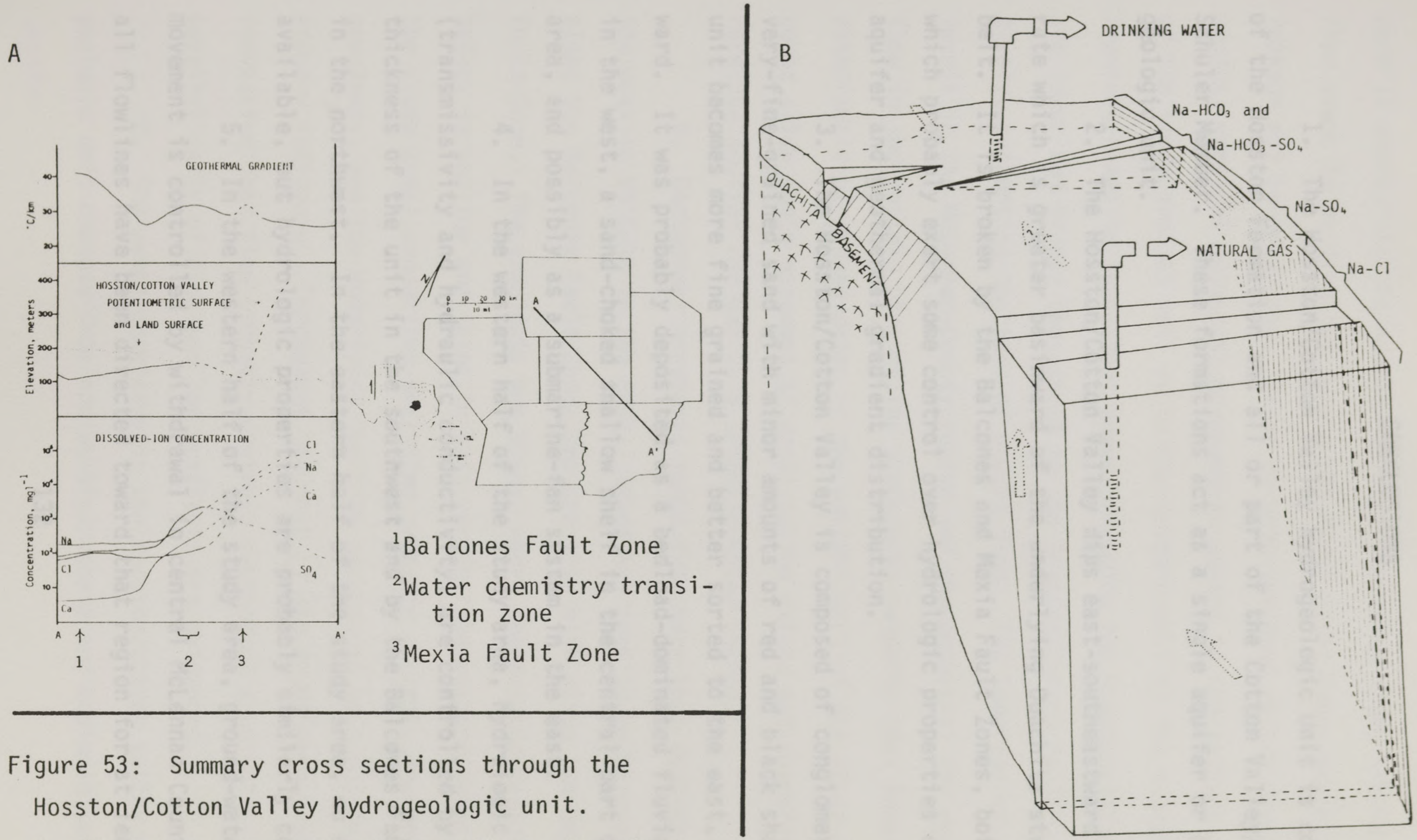


Figure 53: Summary cross sections through the Hosston/Cotton Valley hydrogeologic unit.

A. Variations in geothermal gradient, dissolved-ion concentrations and potentiometric surface. B. Schematic block diagram showing possible directions of ground-water flow (arrows), chemical composition of the ground water and optimum area for low-temperature geothermal ground water (striped area on left side of diagram).

CONCLUSIONS

1. The Hosston/Cotton Valley hydrogeologic unit is composed of the Hosston Formation and all or part of the Cotton Valley/ Schuler Member. These formations act as a single aquifer or hydrogeologic unit.

2. The Hosston/Cotton Valley dips east-southeastward at a rate which is greater basinward of the underlying Ouachita structural belt. It is broken by the Balcones and Mexia Fault Zones, both of which probably exert some control over hydrologic properties of the aquifer and geothermal gradient distribution.

3. The Hosston/Cotton Valley is composed of conglomeratic to very-fine-grained sand with minor amounts of red and black shale. The unit becomes more fine grained and better sorted to the east, or basinward. It was probably deposited as a bedload-dominated fluvial system in the west, a sand-choked shallow shelf in the central part of the area, and possibly as a submarine-fan system in the east.

4. In the western half of the study area, hydrologic properties (transmissivity and hydraulic conductivity) are controlled by net-sand thickness of the unit in the southwest and by the Balcones Fault Zone in the northwest. In the eastern half of the study area, no data were available, but hydrologic properties are probably similarly controlled.

5. In the western half of the study area, ground-water movement is controlled by withdrawal in central McLennan County, and all flowlines have been directed toward that region for at least the

past 15 years. In the eastern half of the study area, ground-water flow seems to be directed toward the Mexia Fault Zone, where upward leakage may be occurring. Based on pressure-head versus depth graphs, vertical potential movement is upward in the eastern half of the study area as well as in the western half of the study area. Pressure heads in formations above and below the Hosston/Cotton Valley are lower and higher than those in the Hosston/Cotton Valley, respectively, supporting the idea of upward flow. The lowering of water levels in the McLennan-County region and the potential for upward flow in the eastern part of the study area suggests that long-term withdrawals of ground water in the western part of the study area could allow updip movement of deep, saline water, and therefore ruin the aquifer for use as a drinking-water source.

6. Geothermal gradients range from more than 40°C/km in the west to 25°C/km in the east. Gradients seem to be highest along the Balcones Fault Zone, and are also high along the Mexia Fault Zone. The gradients are higher where the Hosston/Cotton Valley is shallow and thin; in this region (the western third of the study area) conductive heat flow probably controls geothermal gradients, and the underlying Ouachita structural belt may be the primary influence. Throughout the rest of the study area, forced-convective heat flow probably controls geothermal gradients; parallel cells of high and low gradients are evidenced.

7. The water chemistry in the Hosston/Cotton Valley hydrogeologic unit changes from sodium-bicarbonate and sodium-bicarbonate-

chloride-sulfate to sodium-sulfate in the central part of the study area, and then to sodium-calcium-chloride and sodium-chloride in the eastern half of the study area. The evolution of the sodium-sulfate water is probably due to oxidation of hydrogen sulfide (H_2S), with concurrent dissolution of calcite and feldspar alteration to clays or cation exchange on clay minerals. The source for the H_2S is probably the deep basinal waters to the east. This requires differential movement of gas and water since there is no similar increase in chloride concentration; chloride is the dominant anion in the deep basinal waters. In the western half of the study area, local anomalous water chemistry occurs along faults in the Balcones Fault Zone, suggesting contamination along these faults or restriction of circulation which has allowed anomalous water chemistry to develop.

8. The optimum region for development of low-temperature geothermal ground water in the study area, notwithstanding the fact that the aquifer is already being stressed in McLennan County where discharge is greater than recharge, is along the area of high gradients stretching from eastern McLennan County through central Falls County and northeastern Milam County. In the eastern part of this optimum area, dissolved-solids content of the ground water is high, and is predominantly sodium and sulfate, rendering the water unsuitable for drinking. Although actual water temperatures are lower, in central McLennan County gradients are high and water quality is good, and a program of water withdrawal for heat extraction with subsequent reinjection should help prevent further decline in storage in the aquifer.

APPENDIX I: Energy from Low-Temperature Geothermal Ground Water

According to E.G. & G. Idaho, Inc. (1978) the minimum water temperature with energy available for use is 47°C as calculated from:

$$\Delta t = (0.6 \times t_s) - 21.1°C$$

where Δt = maximum economical temperature drop

t_s = source temperature

This formula assumes an efficiency of 69% of the water temperature, a number apparently based on heat-exchanger efficiencies. Ground-water heat pumps, on the other hand, can operate on a negative temperature differential (that is, can extract heat from a source which is colder than the desired ambient temperature), suggesting that substantial amounts of energy are available from geothermal water as defined in this report. Hildebrandt and Elliot (1979) and Bywaters and others (1979) explain in detail designs for various types of buildings in Houston and Dallas, Texas, respectively, in which heat pumps alone or with a thermal storage mass are used for space heating.

In the study area, the region with potable water having temperatures suitable for space heating with ground water is much larger for ground-water heat-pump systems than that for conventional heat-exchange systems. However, heat pumps are expensive, and for purposes of illustration, design calculations for the conventional heat-exchange system provide insight into the relatively large amount of energy available from the relatively small amount of ground water necessary for space heating an "average" residence.

Based on E.G.&G. Idaho, Inc. (1978) formulas, the amount water needed to heat a 167 m^2 home considered an "Average Residence" (a construction class between classes of "Average Energy Efficiency" and "Poor Energy Efficiency", not defined in referenced publication) is calculated below, assuming an initial water temperature of 50°C.

$$t = (0.6)(122) - 70 = 3.2°F$$

$$HL_{max} = 500(t - t_0) = 500\ (70 - 56) = 7000 \text{ Btu hr}^{-1}$$

where HL_{max} = maximum heat load

t = inside design temperature

t_0 = mean minimum air temperature, Waco, Texas

$$H = 1.25\ (HL_{max}) = 1.25\ (7000) = 8750 \text{ Btu hr}^{-1}$$

where H = delivered heat

$$W = \frac{H}{(500)(\Delta t)} = \frac{8750}{(500)(3.2)} = 5.5 \text{ gallons per minute (21 liters per minute)}$$

where W is fluid flow rate

This is a relatively small fluid-flow rate; however, because a four-person family uses only 760 to 1140 liters per day (U.S. Environmental Protection Agency, 1974, p. 15), a program for reinjection of the water after heat extraction is advisable.

APPENDIX II: Stratigraphic, Hydrologic and Geothermal Data

Appendix IIA contains a description of the well control used for the geologic, hydrologic, and geothermic parts of the study. The American Petroleum Institute reference numbers have the following prefixes:

County	Prefix
Bell	42-027
Falls	42-145
Limestone	42-293
McLennan	42-309
Milam	42-331
Robertson	42-395

Appendix IIB contains the stratigraphic data used in the geologic part of the study. All values are in meters; tops and bases and elevation are in meters above or below sea level. The symbol "F" in the table indicates a fault.

Appendix IIC lists hydrologic properties data. The following symbols are used:

Symbol	Meaning
E	Estimated transmissivity
V	Average of several tests
R	Values reported in the literature or in TDWR files.
A	Transmissivity adjusted for partial penetration by: $T_m / x = K$; $K \times b = T_a$

T_m = measured transmissivity
x = length of screened interval
K = hydraulic conductivity
b = total aquifer net sand
T_a = adjusted transmissivity

Appendix IID lists water level data used in construction of potentiometric-surface maps. All measurements are in meters; "1" indicates measurement affected by recent pumping and "2" indicates measurement may not be valid for other reasons. A "3" following a well number indicates the well is completed in both the Hensel Sand and the Hosston Sand. An "*" following the county name indicates that the unique numbers do not correspond to the Bureau of Economic Geology Low-Temperature-Geothermal project well numbering system, as do all other well identifiers used in this study. Corresponding TDWR reference numbers are listed separately for these counties at the end of Appendix IID.

Appendix IIE lists bottom-hole pressure data used in construction of potentiometric-surface maps and in development of pressure-head-versus-depth graphs. Unit abbreviations are as follows:

Symbol	Unit
G	Glen Rose Limestone
H	Hosston/Cotton Valley hydrogeologic unit
S	Smackover Limestone

"ISIP" and "FSIP" are initial and final shut-in pressures, respectively, and are reported in pounds per square inch. Astericked values are those Hosston/Cotton Valley data used in contouring the potentiometric surface.

Appendix IIF lists geothermal gradients calculated from bottom-hole temperatures. The unit abbreviations are as follows:

Symbol	Unit
P	Paleozoic-age rocks
H	Hosston/Cotton Valley hydrogeologic unit
G	Glen Rose Limestone
S	Smackover Limestone

An "*" indicates the values were taken from a temperature log. A "'" symbol following the unit designation indicates the depth is with 5 meters or less of the top of the formation, and thus may not truly reflect temperatures in that formation.

Appendix IIG lists geothermal gradients calculated from produced-water temperatures. All data are from the Hosston/Cotton Valley hydrogeologic unit. An "*" indicates that the only depth available was that of total depth, and geothermal gradient was based on that rather than the middle of the production interval.

Appendix IIA: Well control, Falls-County area, low-temperature geothermal ground water.

No.	Operator/Driller	Fee/Owner	TDWR No.	API No.
		BELL COUNTY		
1	Emory Dunnam	01 J. E. Hunt	58-02-102	00057
2	Texas Water Wells	02 City of Holland	58-05-902	
3	J.L. Myers	02 BMF Water Supply		
4	J.L. Myers	04 City of Belton	40-61-401	
5	J.L. Myers & Sons	02 Brazos River Electric	40-61-504	
6	Wes-Tex Tool Service	01 Taylors Valley deep well	40-61-901	
7	J.L. Myers	01 BCID	40-62-801	
8	Texas Water Wells	01 R. Wilson Plastics	40-62-102	
9	J.L. Myers	04 City of Temple	40-62-101	
10	J.L. Myers	02 Temple Airport	40-53-902	
11	Wes-Tex Tools	01 Pendleton WSC	40-54-401	
12	A.B. Johnson	01 Howard	40-45-903	
13	Watts Drilling	Belton Reservoir	40-53-506	
14	Layne Texas Co.	02 City of Troy	40-54-601	
15	J.L. Myers Sons	City of Temple	40-61-508	
16	J. L. Myers Sons	J.G. Nash	40-53-704	
17	Layne Texas Co.	City of Rogers	58-07-701	
19	Hervey Meadows	Leon River Farms	58-05-403	
21		01 Bell-Falls-Milam WSC	58-06-601	
22		T.D. Meacham	58-07-301	
23	J.L. Myers Sons	U.S. Army Corps of Engs.	40-61-105	
24	J.L. Myers Sons	01 O & B Water Supply	40-55-701	
27	U.S. Army	01 McCloskey Hospital	40-62-401	
28	Gilchrist Drlg. et al	01 D.L. Curb Fee	40-59-801	
29	Shell	01 Massie	40-59-901	00067
30	J.L. Myers & Sons	01 Brazos River Electric	40-61-503	
31	Layne Texas Co.	01 City of Temple	40-61-507	

Appendix IIA, continued.

No.	Operator/Driller	Fee/Owner	TDWR No.	API No.
		Bell County, cont.		
32	Layne Texas Co.	03 City of Temple	40-61-509	
37	C.M. Stoner Drlg.	Moffat WSC	40-53-505	
38	A.N. Edwards	City of Troy	40-54-501	
39	Watts Drlg. Co.	Little Elm WSC	40-54-502	
40	Texas Water Wells	U.S. Army Corps of Engs.	40-61-101	
41	Layne Texas Co.	U.S. Army Corps of Engs.	40-60-601	
42	Wiegand Drlg.	U.S. Army Corps of Engs.	40-60-801	
43	Wiegand Drlg.	U.S. Army Corps of Engs.	40-60-902	
44	Wiegand Drlg.	U.S. Army Corps of Engs.	40-60-903	
45	Wiegand Drlg.	U.S. Army Corps of Engs.	40-60-904	
46	Wiegand Drlg.	U.S. Army Corps of Engs.	40-60-905	
47		City of Belton	40-61-405	
48		City of Belton	40-61-403	
49	D.C. Hammell	City of Belton	40-61-402	
50	J.L. Myers	03 City of Belton	40-61-703	
51	Texas Water Wells	02 BCWID (Little River)	58-06-102	
53	Wes-Tex Tool Service	East Bell WSC	40-63-501	
55	Triangle Pump & Supply	Acres WSC	40-62-501	
56	J.L. Myers	02 Pendleton WSC	40-50-5b	
59		City of Belton	40-61-104	
60	Fowler Drlg.	Harvey Bacon, Jr.	40-59-301	
61	J.B. Farquharson	Wineford Cosper	40-59-701	
62			58-03-501	

Appendix II A, continued.

No.	Operator/Driller	Fee/Owner	TDWR No.	API No.
		FALLS COUNTY		
1	J.L. Myers	01 Perry WSC	39-33-604	
3	J.L. Myers	01 Golinda WSC	40-48-201	
4	Wes-Tex Tool Service	01 Mooreville WSC	40-47-602	
5	Chilton Water Well Co.	02 City of Chilton	40-48-801	
7	Key Drilling Co.	01 Durango-Cego WSC	40-56-102	
8	A.H. Bell	01 C.L. Trice	40-56-302	
10	J.L. Myers	01 Westphalia water well	40-64-101	
12	Humble Oil & Refining	02 Emma Pieper	40-64-201	00540
13	Humble Oil & Refining	01 Eleanor Carroll	40-64-102	00544
14	Delhi-Taylor Oil	01 J.A. Cobb	39-57-402	00325
15	W.P. Luse	01 Fred Voltin	40-64-701	00548
17	McAlester Fuel Co.	01-A Condy Nichols		00260
18	Cockburn-Zephyr	01 Dr. N.D. Buie	39-42-801	00263
19	Dail Goodson et al	01 J.G. Bargainer	39-50-110	00308
20	Hinton Producing	01 N.J. Snider		30101
21	Seaboard Oil Co.	01 J.E. Green	39-43-801	
22	W.M. Brelsford et al	01 McHenry-Eisen		00289
25	Texas Water Wells	01 Tri-County WSC	39-33-901	
26	H.C. Cockburn et al	01 Gilliam		00211
28	Grelling Oil Invest.	01 T.J. White		00577
29	Amoco Production	01 Grace Kelly		30096
31	Jake L. Hamon	E.C. & B. Grazing Assoc.		
32	Jake L. Hamon et al	03 Ezell		30081
34	Hammon-Wiggins	01 Julia Allen		30086
35	Layne Texas Co.	01 T.H.S. Memorial Hospital		
36	Sun Oil (H.B. Glass)	01 G. DeGraffenreid (City of Chilton)	40-48-501	
37	H.G. Johnson	Sanitarium Drug Co.	39-41-602	

Appendix II A, continued.

No.	Operator/Driller	Fee/Owner	TDWR No.	API No.
		Falls County, cont.		
38	H.G. Johnson	City of Marlin (Pavillion)	39-41-604	
39	Layne Texas Co.	01 City of Lott	40-56-301	00471
40	Hammon-Wiggins	01 Ezell		30078
41	Layne Texas Co.	01 City of Rosebud	40-64-601	00547
42	J.L. Myers Co.	01 West Brazos WSC	40-40-8a	
43	J.L. Myers Co.	04 Tri-County WSC	39-33-3a	
44	McClinton Drlg.	01 A.H. Rowen	40-48-5a	
		LIMESTONE COUNTY		
1	Spence-Hughes	01 Paul Collins	39-17-601	00411
2	Henry Gossett	01 Olin Reedy		
4	Pan American Petroleum	01 Forsythe		00974
6	J.L. Myers	01 City of Prairie Hill	39-18-802	
7	Hunt Oil Co.	01 Union Central Lic.	39-19-701	00394
8	The Texas Co.	W.A. Keeling		00393
9	Hunt Oil Co.	01 C.R. & Guy Yeleurton		
11	Farrell Drlg.	01 J.R. Gilliam	39-26-601	00425
12	M.M. Miller	01 J.C. Rogers		
13	O.W. Killiam	01 W.D. Stone	39-17-101	00103
14	A.F. Tinney	01 A.R. Reed		
15	Humble Oil & Refining	01 L.W. Rogers		
16	Gulf Oil/F. Bryant	01 Beeville Est.	39-27-501	
17	Byrd-Frost-Byrd Oil Co.	01 Maddox		00160
19	Gregg-Tex Gasoline	01 J. Baker		
20	Humble Oil & Refining	01 W.L. Hernstadt Est.		00556
21	Union	Jackson		00597

Appendix II A, continued.

No.	Operator/Driller	Fee/Owner	TDWR No.	API No.
		Limestone County, cont.		
22	McAlester Fuel Co.	01-A Vesta Wilson		
23	McAlester Fuel Co.	01-A J.F. Jackson		
24	P.G. Lake, Inc.	01 Nolan Wiley		00603
25	H.L. Hunt	01 James Gibson Heirs		00966
26	Pan American Petroleum	01 E.H. Williams		00637
27	Lone Star Prod. Co.	01 Billy S. Criswell	39-35-802	00447
28	Foster-Zephyr Oil Co.	01 F.F. Wilson		
29	H.L. Long	01 A.D. Bates et al		
30	Sun Oil Co.	01 Cyrus F. Smythe		
31	O.W. Killiam	01 R.L. Nance Est.		00533
32	Lomay-Brown	01 J.L. Reagan		
33	Key Prod.	01 R.C. Archer		
35	Cape Drilling Co.	04 J.F. Jackson	39-29-803	30074
36	Mitchell & Humphrey	01 Burleson Gas Unit	39-37-301	
37	Phillips Petroleum	01-A Bradley "A"		30083
38	B.L. Herd & R. Hedge	01 Gant	39-38-801	30049
39	J. Gourley et al	01 Ethel Barron		
40	Getty Oil Co.	01 Frank B. Bell	39-29-301	00980
41	The Pure Oil Co.	16 W.H. Kendricks	39-20-601	
42	Mobil Oil Corp.	01 A.W. Whilte Unit	39-37-601	
43	Stanolind Oil & Gas	01 T. Norris		
44	Herd-Beaird-Tufco	01 Gibson		30133
45	Cities Service Oil Co.	01 Dorothy Bounds		00037
46	Bee Kay Co.	01 C.R. Yelverton		00346
48	Stephen E. Collins et al	01 R.W. Oliver		30021
49	W.W. Wise Drilling, Inc.	01 W.T. Lattner		00099
50	Watburn Oil et al	01 Wilma Jean Koch		00095
52	H.L. Gist, Jr.	01 J.E. Sharp		00115
53	McGuire Russell	01 Pierce Wisdom		00126

Appendix II A, continued.

No.	Operator/Driller	Fee/Owner	TDWR No.	API No.
		Limestone County, cont.		
54	Brown Oil & Gas Co.	01 F.B. Parsons		30013
55	Lone Star (Mitchell Energy)	01 McGillivray Muse		30040
56	Vaughn Petro.-S.F. Collins	01 Easterling Gas Unit		00969
59	Westpan Hydrocarbon Co.	01 Billy Crider		00076
61	Jake L. Hamon	01 Kennedy		30045
62	Dallas Expl.	01 Garland Turner		30077
64	T.D. Humphrey, Jr., et al	01 J.G. Climer		00078
65	T.D. Humphrey, Jr., et al	01-A O.A. Bogeman		00079
66	Humble Oil & Refining	01 Fallon Gas Unit No. 1		00080
69	Cape Randy	03 J.F. Jackson		30068
71	McAlester Fuel Co.	01 Ila White et al		00081
72	Jake L. Hamon et al	01 White		00979
73	Jake L. Hamon et al	01 Keris		30003
74	W.B. Hinton et al	01 R.W. Carter		00448
76	Union Prod.	01 R.B. Tillman		00982
77	Thornton Lomax, Jr., et al	05 W.J. Buttrell		00541
78	Thornton Lomax, Jr., et al	01 M.N. Bennett		00536
79	J. Burns Brown et al	01 Lullene Reagan		00535
81	W.R. Hughey et al	01 F.D. Connell		00646
82	Ralph Spence	01 W.S. Hunnicutt		00543
83	Pan American Petroleum	01 W.S. Hunnicutt		00544
85	Three States Natural Gas	01 T.E. Reynolds		00613
86	Ralph Spence	R-1 C.C. Favors Est.		30080
87	Ralph Spence	01 Favor Est.		00591
88	W.W. Wise Drlg.	01 W.C. McPherson		00602
89	W.W. Wise Drlg.	01 Jessie Pearl Wright		00624
90	Texas	01 Lula Mason		00612
92	Wise Operating Co. (Three States Natural Gas)	01 Jacoby & Harris (Harris Gas Unit No. 1)		00631

Appendix II A, continued.

No.	Operator/Driller	Fee/Owner	TDWR No.	API No.
		Limestone County, cont.		
93	Herd Prod.	01 Connell		30146
94	Lone Star Producing Co.	01 M. Muse		30040
95	Stephen W. Schneider & Rex Corey	01 M.M. Peters		30022
96	Fair Oil Co., Inc.	01 O.K. Sims		30087
97	Pennzoil Producing Co.	01 James Jackson		30038
98	Ralph Spence	01 Reynolds Unit		00542
99	Herd-Beaird-Tufco	01 Standley		30141
100	Sundance Oil Co. & Rebpet, Inc.	01 I.V. Carpenter		30144
101	Continental Oil Co.	01 Nick Hardeman		30082
102	Ralph Spence	01 Floyd Lowery		00722
103	Mesa Petroleum Co.	01 F.D. Connell		30130
		McLENNAN COUNTY		
2	C.M. Stoner	01 Bold Springs WSC	40-15-901	
3	H.B. Glass	01 Ross WSC	40-24-102	
4	Layne Texas Co.	01 Leroy-Tours-Gerald WSC	40-24-301	
5	J.L. Myers	01 J.R. Patterson	40-24-502	
6	J.L. Myers	Youngbloodflowers	40-24-704	
8	Simon Korshoj	01 R.J. Ferguson	39-17-401	
9	J.L. Myers Sons	01 Axtell water well	39-17-701	
10	E.J. Muth	01 Freeman	40-29-103	
11	C.M. Stoner	03 Midway Water Co.	40-39-106	
12	Pure Milk Co.	01 Garrison	40-31-612	
13	J.L. Myers	01 Dr. Barnes	40-39-203	
14	Layne Texas Co.	03 Texas Power & Light	39-33-102	

Appendix II A, continued.

No.	Operator/Driller	Fee/Owner	TDWR No.	API No.
		McLennan County, cont.		
16	Mae Belcher	01 E.W. Smyth	39-26-801	
17	Delta Drilling	01 Carl Horstman	40-37-902	
18	J.L. Myers	02 Tilton J.B. Todd	40-38-502	
19	C.M. Stoner	01 Spring Valley WSC	40-38-801	
21	West Texas Tool	01 Levi WSC	40-40-702	
22	Henry C. Paine	01 H.C. Eubanks	40-47-101	
23	J.L. Myers	01 City of Moody	40-46-402	
24		City of West	40-16-401	
25	Hervey Meadows & Sons	W.B. Bass & Sons	40-21-902	
27	Triangle Pump & Supply	East Crawford WSC	40-29-601	
28			40-22-905	
29			40-31-102	
34		City of Waco	40-31-601	
37	H.B. Glass	01 Ross WSC	40-24-101	
38			40-24-302	
41	Layne Texas Co.	State of Texas	40-24-802	
43	Layne Texas Co.	City of Bellmead	40-32-102	
44	J.L. Myers	City of Bellmead	40-32-103	
45	Layne Texas Co.	General Tire & Rubber	40-32-403	
46	Layne Texas Co.	General Tire & Rubber	40-32-404	
48	J.L. Myers	City of Waco	40-32-501	
50	Layne Texas Co.	02 Texas Power & Light	39-25-402	
51	J.L. Myers	01 City of Mart	30-25-501	
54	J.L. Myers	Waco Memorial Park	40-39-302	
55	J.L. Myers	Lorena WSC	40-39-702	
56	Layne Texas Co.	01 Texas Power & Light	39-33-101	
57	J.L. Myers	Meier Settlement WSC	39-33-104	
58	C.M. Stoner	Elm Creek WSC	40-46-801	
59	(Reported in Myers, 1963; not identified except by location)			

No.	Operator/Driller	Fee/Owner	TDWR No.	API No.
		McLennan County, cont.		
60	(Reported in Myers, 1963; not identified except by location)			
61	J.L. Myers	03 City of West	40-16-403	
62	Pure Milk Co.	01 Water well	40-31-602	
63	Falcon Oil Co.	01 Henry Mattlage, Jr.	40-28-901	
64	Robert C. Smith & Falcon Oil Corp.	01 H.G. McKethan		00178
65	(Reported in Myers, 1963; not identified except by location)			
66	Key Water Well Drlg.	City of West	40-16-404	
67		Cross Country WSC	40-22-605	
68	C.M. Stoner	Pure WSC	40-24-501	
69	J.L. Myers	02 McLennan Co. WCID	40-24-703	
70	Layne Texas Co.	State of Texas	40-24-803	
71	C.M. Stoner Drlg.	02 Hewitt Water Co.		
72	J.L. Myers	City of Lacy-Lakeview	40-32-104	
73		01 Hog Creek WSC	40-28-302	
74	C.M. Stoner	Midway Water Co.	40-31-701	
75	Layne Texas Co.	Bryan-Maxwell-Bryan	40-31-802	
76	J.L. Myers	H & H WSC	39-25-701	
77	J.L. Myers	01 Riesel MUD	39-33-202	
80	R.F. Caraway	Midway Water Co.	40-31-801	
81	J.L. Myers	Waco Syrian Assoc.	40-39-101	
82		Leroy-Tours-Gerald WSC		
83	J.L. Myers	02 City of Moody	40-46-403	
84	J.L. Myers	Midway School	40-39-104	
85	Key Drilling Co.	01 Rolling Hills Country Club		
86	J.L. Myers	03 Robinson water well	40-40-401	
87	E.H. O'Dowd (R.F. Caraway)	01 O'Dowd (Robinson Water Co.)	40-40-101	
88	A.J. Gorski	01 John H. Kuehl		

Appendix II A, continued.

No.	Operator/Driller	Fee/Owner	TDWR No.	API No.
		McLennan County, cont.		
89	J.L. Myers	02 Prairie Hill WSC	39-17-901	
90	Key Drilling	04 W.C. West		
91	Triangle Pump & Supply	Myers Settlement WSC	39-25-801	
92	Glass	Buchanan	40-31-604	
93	J.L. Myers	City of West	40-16-402	
94	J.L. Myers Sons	M.M. O'Dowd	40-30-901	
95	J.L. Myers Sons	Mt. Carmel Center	39-25-101	
96	J.L. Myers Sons	Elk-Oaklake WSC	39-25-102	
99	H.B. Glass	C.S. Lankart	40-40-804	
106	E.A. Glass	W.H. Cast	40-46-602	
		MILAM COUNTY		
1	Layne Texas Co.	01 Milam County Water District (City of Buckholts)	58-07-901	
2	Groginski & Marcus	01 G. Baskin		
3	Rimrock Tidelands	01 W. Crawford	59-01-301	00066
4	D. Harrison	01 A. Smith et al		00393
5	D. Harrison	01 G. Schram		00404
9	Texas Gulf Sulfur	01 Baker		
10	Shell Oil	01 Neil Ross		
14	Wagner	01 Grienert		
19	B.B. Orr	01 T.S. Henderson Est.		00238
20	Byrd Oil Co.	02 M. Blakely		00233

Appendix II A, continued.

No.	Operator/Driller	Fee/Owner	TDWR No.	API No.
		ROBERTSON COUNTY		
1	Continental Oil Co.	01 C.M. Campbell		
2	R.J. Caraway	01 Herman Yezak		
3	Union Prod. Co.	01 Gibson		
4	Shell Oil Co.	01 D.I. Hamilton		00016
5	Skelly Oil Co.	01 G. Williams		
6	Adobe Oil Co.	01 R.L. Reagan		
7	Mobil Oil Corp.	01 R.L. Reagan		
8	Humble Oil & Refining	01 J.L. Blair		
9	Texas Gas Expl. & Dunlap	01 Mozelle Kellogg		
14	B.B. Orr	02 Abraham		
15	B.B. Orr	03 George Abraham		30012
16	Jake L. Hamon	01 Corn		30022
17	Gulley, Long & Hedge Drlg.	01 J.J. Bray		00171
18	K.L. McHenry	01 George Abraham		00029
19	Pan American Prod. Co.	01 W.H. Ables		00057
20	Magnolia Petroleum Co.	01 Pauline Doremus		00062
22	Ada	01 W.T. Anderson et al		30009
23	Skelly Oil	01 G. Williams		30017
24	Adobe Oil & Gas and B.L. Herd	01 John F. Ziegleschmid		30201
25	Louisiana Land & Expl.	01 W.C. Grace		30204

Appendix II B: Stratigraphic data, Falls County area study.

No.	Datum Elevation	Top Sligo Fm.	Top, Hosston/ Cotton Valley	Base, Hosston/ Cotton Valley	Top, Paleozoic	Net Sand, Hosston/Cotton Valley
			BELL COUNTY			
1	246.6				33.2	
2	168.2	-463.9	-493.2	<-569.1		> 54.9
3	135.0	-578.2	-606.2	<-726.0		>100.6
4	160.0	-147.8	-165.2	<-197.5		> 24.4
5	153.6	-169.5	-189.6	<-225.9		> 24.4
7	187.1	-458.1	-485.5	<-534.0		> 35.1
8	215.5	-272.5	-288.0	<-338.9		> 35.1
9	230.7	-302.7	-311.8		-391.1	54.9
10	209.7	-121.3	-128.0		-178.9	39.6
11	242.3		-182.6		-258.2	47.2
12	226.8		-145.1		-199.9	41.1
13	216.4		-84.1	<-118.9		> 22.9
14	213.4	-292.6	-309.1		-340.8	20.7
24	183.5	-534.6	-552.6	<-627.3		> 54.9
27	205.7	-376.4	-387.7		-499.9	97.5
28	252.7	88.7	67.4		0.3	40.2
29	191.1	20.4	5.2		-22.3	21.3
30	152.4	-172.5	-192.0		-224.9	25.3
31	160.9	-163.7	-183.5		-214.0	18.3
32	158.8	-167.3	-182.6		-219.2	22.9

Appendix II B, continued.

No.	Datum Elevation	Top, Sligo Fm.	Top, Hosston/ Cotton Valley	Base, Hosston/ Cotton Valley	Top, Paleozoic	Net Sand, Hosston/Cotton Valley
			FALLS COUNTY			
1	146.0	-762.9	-791.3	<-966.8		>121.0
4	167.0	-540.7	-562.4		-621.5	44.8
5	141.7	-642.5	-667.8		-733.0	36.6
7	171.0	-614.2	-634.3	<-672.7		> 30.2
8	122.5	-718.1	-747.7	<-799.5		> 39.6
10	177.4	-681.5	-704.4	<-755.3		> 29.0
12	132.3	-705.6	-719.0	<-747.7		> 21.3
13	153.0	-707.7	-719.6		-946.4	161.5
14	121.9	-877.8	-915.6	<-1104.0		> 158.5
15	133.8	-719.6	-763.2			
17	110.0	-1255.5	-1281.7	-1702.3		314.6
18	122.5	-1151.5	-1192.1	-1701.1		355.1
19	100.0	-1134.5	-1171.1	<-1267.1		> 71.6
20	119.8	-1547.8	-1599.3	-2364.3	-2516.7	608.1
21	132.6	-1580.4	-1629.2	<-1756.9		> 85.3
25	144.5	-804.1	-817.8	<-1002.5		> 129.5
26	124.4	-1301.5	-1335.6	-1777.6		271.3
28	136.6	-1720.0	-1771.5	-2431.7		474.0
29	143.9	F	F -1656.0	-2211.6		F 377.0
31	144.8	-1748.6	-1800.8	-2554.2		522.7
32	151.8	-1764.8	-1819.4	-2595.4		515.1
34	150.9	-1780.0	-1835.8	-2611.5		529.4
35	119.5	-874.2	-900.1	<-1064.7		> 109.7
41*	115.8	-864.1	-894.6	<-1009.5		
42	139.6	-586.1	-607.5	< -670.6		> 47.5
43	170.1	-790.7	-812.3	< -970.5		> 108.2

Appendix II B, continued.

No.	Datum Elevation	Top, Sligo Fm.	Top, Hosston/ Cotton Valley	Base, Hosston/ Cotton Valley	Top, Paleozoic	Net Sand, Hosston/Cotton Valley
				LIMESTONE COUNTY		
1	163.4		-647.4		-770.8	100.6
4	153.6	-2229.9	-2284.5		-2481.4?	134.1
6	181.4	-871.1	-890.9	<-1020.2		> 86.9
7	167.6	-993.6	-1024.7	-1306.1		202.7
8	166.4	-1086.3	-1119.5	-1398.1		205.1
9	160.0	-1417.3	-1454.5	<-1495.3		> 33.5
11	158.8	-945.2	-972.3	-1232.6	-1304.2	179.8
12	163.4	-1110.1	-1148.8	-1473.4		222.5
13	161.5	-1116.2	-1152.1	<-1211.9		> 35.1
14	167.3	-1404.5	-1445.4	<-1481.9		> 18.3
15	153.9	-1524.0	-1562.1	-2179.0		408.4
16	172.2	-1271.6	-1313.4	<-1507.8		>120.4
17	141.7	-1521.9	-1563.3	<-1626.7		> 45.7
19	157.0	-2028.1	-2089.1	<-2283.3		>137.2
20	152.7	-1850.7	-1892.5	-2240.0		253.0
21	124.1	-1884.0	-1931.8	-2707.5	553.2	553.2
22	122.5	-1875.4	-1923.0	<-2109.8		>138.7
23	124.1	-1887.6	-1934.9	<-2101.3		>114.3
24	136.2	-2028.4	-2078.4	<-2180.5		> 66.4
25	132.9	-2097.0	-2149.8	-3152.2		852.8
26	141.7	-2295.1	-2365.2	-3317.7		761.4
27	140.2	-1328.9	-1369.5	-1822.7		338.9
28	164.3	-1622.8	-1667.0	-2100.4		336.8
29	145.7	-1900.4	-1957.4	<-2142.1		>103.6
31	142.0	-1783.1	-1836.7	<-1867.5		> 25.9
32	136.6	-1835.5	-1890.4	-2681.3		562.4
35	125.9	-1902.6	-1949.2	<-2048.9		> 64.0
36	133.8	-2036.4	-2097.3	-2964.5		626.4

Appendix II B, continued.

No.	Datum Elevation	Top, Sligo Fm.	Top, Hosston/ Cotton Valley	Base, Hosston/ Cotton Valley	Top, Paleozoic	Net Sand, Hosston/Cotton Valley
			Limestone County, cont.			
37	126.8	-1895.6	-1944.3	-2754.5		570.0
38	145.4	-2416.5	-2482.0	< -3050.1		>441.4
39	141.7	-1615.1	-1650.5	< -1756.0		> 74.7
40	152.7	-2032.1	-2093.7	-2980.9		716.3
41	158.2	-1524.3	-1565.8	-2351.8	-2478.3	
42	118.3		<-2147.9	-3044.0		>667.5
43	157.9	-1480.4	-1532.2	-1966.6		318.5
44	139.0	-2406.1	-2508.2	-3543.9		786.1
53	125.3	-1684.6	-1733.7	< -1948.9		>155.4
54	148.9	-1949.5	-2008.9	-2781.6		595.9
56	161.4	-2080.6	-2144.0	-2993.1		551.1
59	124.4	-2259.2	-2321.7	< -2388.1		> 49.7
73	137.5	-1879.7	-1930.3	-2825.2		627.9
83	136.6	-1909.0	-1967.8	-2864.5		681.2
94	161.2	-2086.1	-2146.7	-3022.4		649.2
95	128.9	-1977.5	-2035.1	-2910.5		696.5
96	113.4	-2088.2	-2153.1	<-2350.9		>166.1
97	161.5	-1935.5	-1990.3	-2892.6		722.4
98	142.0	-1924.5	-1982.1	<-2083.6		> 83.8
99	132.3	-2390.5	-2461.9	-3498.8		766.6
100	136.6	-2462.8	-2570.1	<-2910.8		>248.4
101	168.9	-1916.3	-1980.6	-2834.3		607.5
102	134.4	-1989.1	-2048.9	<-2186.6		>112.8
103	125.9	-2028.4	-2090.6	-2929.1		675.1

Appendix II B, continued.

No.	Datum Elevation	Top, Sligo Fm.	Top, Hosston/ Cotton Valley	Base, Hosston/ Cotton Valley	Top, Paleozoic	Net Sand, Hosston/Cotton Valley
			McLENNAN COUNTY			
2	182.3		-311.5		-378.6	40.2
3	174.7		-443.5	<-516.6		>44.5
4	150.9		-579.1	<-720.9		>89.9
5	147.2		-538.0	<-596.5		>32.6
6	152.4		-487.7		-548.0	39.6
8	173.7		-640.1		-803.1	93.6
9	163.1		-621.5		-772.7	65.5
10	224.9		-80.5		-117.7	25.9
11	199.6		-304.8	<-357.5		>38.1
12	125.0		-461.8	<-545.6		>39.6
13	179.8		-368.8		-435.9	53.3
14	130.8	-632.8	-652.3	<-738.2		>50.3
16	161.8	-898.9	-926.3	<-932.4		
17	212.8		-111.3		-129.5	11.6
18	188.1		-175.3		-194.2	16.8
19	213.4		-196.6		-229.2	21.3
21	125.9	-556.9	-575.2	<-648.6		>50.0
46	123.4		-508.4	<-580.6		>53.6
50	139.6		-620.0	<-759.6		>77.7
51	150.3	-666.6	-691.0	<-819.3		>94.5
56	125.0	-629.4	-659.0	<-737.6		>44.2
58	253.0	-205.4	-210.3		-256.0	28.3
61	198.7		-339.2		-403.3	41.8
62	124.4		-445.6	<-502.0		>36.6
63	233.8		-58.2		-92.4	29.0
64	153.0		-199.3		-247.5	36.6
71	168.9		-364.5		-439.2	54.9
77	150.9	-728.5	-748.3	<-925.1		>120.4

Appendix II B, continued.

No.	Datum Elevation	Top, Sligo Fm.	Top, Hosston/ Cotton Valley	Base, Hosston/ Cotton Valley	Top, Paleozoic	Net Sand, Hoss-ton/Cotton Valley
			McLennan County, cont.			
83	236.8		-157.9		-211.2	32.0
85	234.7		-163.4	<-216.1		>32.9
86	143.3		-519.7	<-618.4		>73.2
87	163.1		-514.5	<-565.7		>41.1
88	161.5	-736.1	-756.8	<-905.3		>101.5
89	173.7		-680.9		-834.5	114.3
90	198.1		-347.5	<-405.4		> 41.1
91	160.9	-704.7	-723.0	<-866.2		> 97.5
			MILAM COUNTY			
1	155.4	-788.5	-821.4	<-895.2		>57.9
3	107.0	-1287.5	-1346.3	-1791.3	-1889.5	402.3
4	143.3	-829.1	-893.1		-1212.5	131.1
5	135.6	-972.3	-1016.2		-1415.8	273.4
9	135.6	-1752.6	-1792.2		-2453.6	317.0
10	142.0	-2507.0	-2598.7		-3312.0	442.0
14	163.7	-662.0	-713.2		-951.9	173.7

Appendix II B, continued.

No.	Datum Elevation	Top, Sligo Fm.	Top, Hosston/ Cotton Valley	Base, Hosston/ Cotton Valley	Top, Paleozoic	Net Sand, Hosston/Cotton Valley
			ROBERTSON COUNTY			
1	95.7	-1678.5	-1748.9	-2332.9		466.3
2	139.9	-1699.6	-1750.5	-2472.2		428.2
3	111.3	-2136.6	-2217.4	<-2342.4		>79.2
4	144.2	-2590.5	-2692.0	-3620.1		635.5
5	150.0	-2109.2	-2184.8	-3087.0		542.5
6	148.7	-2230.2	-2350.0	-3338.2		630.9
7	145.7	-2254.3	-2348.5	-3364.1		777.2
8	128.0	-2407.9	-2528.3	-3503.4		762.0
9	103.6	-2576.5	-2667.0	<-2775.5		>89.9
14	131.1	-1940.1	-1995.2	<-2137.0		>99.1
15	137.2	-1936.4	-1993.4	<-2366.8		>301.8
16	148.1	-2031.2	-2091.2	-2991.3		656.8
17	122.2	-2144.0	-2204.3	<-2218.3		> 7.6

Appendix II C: Hydrologic properties, Falls County study area.

No.	Qualifier	Transmissivity (m^2d^{-1})	Hydraulic Conductivity ($m\ d^{-1}$)	Coefficient of Storage
		BELL COUNTY		
8	E	93	6.0	
14		42	1.1	
27		582	21.5	
31	E	63	2.5	
32	E	58	1.9	
37		96	2.7	
38	V	175	3.8	
39	E	273	9.9	
40		72	7.4	
41	R	130	2.9	9×10^{-5}
42	R	115	2.4	4.3×10^{-5}
43	R	96	2.0	6×10^{-5}
44	R	120	2.6	6×10^{-4}
45	R	130	2.5	4.2×10^{-5}
46	R	92	1.7	5.5×10^{-5}
47		222	9.1	4.3×10^{-4}
48	R	243	10.0	5×10^{-4}
49		231	9.5	2.7×10^{-4}
50	EA	143	2.1	
55	E	58	2.9	
56		87	2.6	
		CORYELL COUNTY		
4	E	6	0.2	
		FALLS COUNTY		
1	A	134	1.3	
4	EA	63	1.6	
7	EA	133	4.8	
35	A	94	0.5	
		WILLIAMSON COUNTY		
12		463	10.4	
13		305	4.0	7.7×10^{-5}
28		432	5.4	

Appendix II C, continued.

No.	Qualifier	Transmissivity ($m^2 d^{-1}$)	Hydraulic Conductivity ($m\ d^{-1}$)	Coefficient of Storage
		McLENNAN COUNTY		
11		71	2.3	
14		20	0.3	
19	E	32	1.6	
23		43	0.9	3.2×10^{-5}
29		52	0.8	
34	R	82	3.0	8×10^{-5}
37		32	0.7	
41		52	0.9	
43		71	1.3	
44	E	81	1.4	
45		56	0.9	
46	R	138	2.2	1×10^{-4}
48	E	55	1.3	
49	A	35	0.4	
50	E	82	1.4	
51	E	199	4.3	
54	E	51	1.7	
55	E	71	2.1	
56	E	25	0.4	
57	E	48	3.2	
58		70	2.7	
59	R	67	1.8	
60	R	62	1.6	8×10^{-5}
65	R	143	3.3	
66		25	0.8	
67	E	12	0.3	
68	EA	48	2.3	
69		139	3.0	
70		47	0.6	
72	E	57	1.1	
73	E	42	1.2	
74		68	2.5	6.6×10^{-5}
75		62	2.0	
76	E	34	0.9	
77	E	98	5.0	
80		66	1.8	6.0×10^{-5}
81		68	3.1	6.0×10^{-5}
83		46	1.1	3×10^{-5}
84		58	1.6	5.9×10^{-5}

Appendix II D: Water levels in the Hosston/Cotton Valley hydrogeologic unit, Falls County area study.

No.	Date	Water Level Elevation (m)
	BELL COUNTY	
2	3-16-66	153.9
	3-20-70	148.5
	3-17-80	133.4[1]
6	3-10-66	147.4
	3-6-70	142.1
	3-13-74	137.5[2]
7	2-21-66	150.5
	3-19-70	144.8
	3-13-74	139.9
	3-17-80	128.9
9	3-10-66	148.3
10	3-14-66	146.0
	2-13-70	139.6
	3-11-74	130.1
	3-14-80	117.0
16	3-10-66	138.3
	3-9-70	131.1
	3-11-74	126.6
	3-14-80	113.1
19	3-15-66	170.9
	3-6-70	166.9
	3-11-74	164.0
	3-17-80	154.9[1]
22	3-11-66	161.8
23	3-7-66	143.5
	3-9-70	136.1
	3-11-74	132.2
	3-14-80	121.0
24	3-11-66	155.8
	3-19-70	150.2
	3-13-74	144.0
32	3-11-66	140.8
	3-4-70	135.3
	3-11-74	136.5
37	1-16-66	142.2
	2-13-70	135.7
	3-11-74	129.4
38	3-21-66	145.9
47	3-10-66	136.4
	3-4-70	133.2
	3-11-74	147.2
50	3-10-66	142.1
	3-7-70	134.2
	3-11-74	134.1
	3-14-80	125.7
51	2-21-66	152.2
	3-19-70	149.8
	3-13-74	124.4[1]
53	3-11-66	151.9
	3-20-70	149.8
54	3-14-66	189.9
	2-23-70	189.3
	3-11-74	189.4
	3-17-80	188.8
59	3-7-66	142.9
	BOSQUE COUNTY*	
1	10-27-66	191.7
2	3-22-66	173.2
3	3-22-66	157.0
4	3-17-66	173.4
	BURNET COUNTY*	
1	3-7-66	317.6[1]
2	3-7-66	306.5
3	3-28-66	384.6
4	3-8-66	312.8
5	3-8-66	368.8
6	3-8-66	337.0
7	3-8-66	335.3
8	3-9-66	382.0
9	3-4-66	268.3

Appendix II D, continued.

No.	Date	Water Level Elevation (m)
	COMANCHE COUNTY*	
1	3-23-66	411.1
2	3-23-66	407.9
3	3-23-66	403.1
4	4-19-66	382.0
5	6-30-66	403.0
6	4-19-66	385.4
7	4-1-66	368.3
8	4-19-66	378.0
9	4-19-66	375.1
10	3-24-66	479.7
11	3-24-66	479.0
12	3-23-66	394.4
13	6-29-66	439.9
14	3-23-66	402.4
15	4-19-66	397.5
16	9-1-66	381.5
17	3-24-66	390.4
18	3-24-66	377.0
19	4-15-66	360.7
20	6-28-66	367.3
21	4-1-66	374.3
22	4-15-66	364.8
23	3-24-66	454.6
24	3-24-66	438.3
25	3-24-66	418.7
26	3-24-66	369.2
27	3-24-66	375.3
28	3-25-66	355.4
29	6-27-66	354.0
30	4-19-66	362.5
31	4-14-66	337.4
32	9-1-66	333.0
33	4-14-66	308.9
34	4-14-66	336.4
35	4-14-66	329.7
36	4-15-66	360.0
37	4-14-66	358.8
38	4-14-66	323.5
39	4-14-66	315.7
40	4-16-66	345.9
41	5-16-66	338.3
42	1-28-66	318.5

No.	Date	Water Level Elevation (m)
	CORYELL COUNTY*	
1	3-30-66	208.7
2	11-24-66	192.0
3	4-5-66	157.3
4	4-5-66	173.6
5	3-10-66	151.0
6	3-11-66	151.6
7	3-10-66	149.6
8	8-26-66	280.2
	EASTLAND COUNTY*	
1	4-7-66	527.1
2	7-4-66	534.7
3	4-7-66	534.2
4	9-1-66	519.6
5	4-7-66	521.5
6	4-1-66	454.7
7	4-1-66	441.1
8	4-6-66	481.2
9	4-6-66	479.5
10	4-6-66	440.5[1]
11	4-6-66	430.0
12	4-1-66	417.6
13	4-6-66	417.9
14	4-1-66	400.7
15	4-1-66	402.6
16	6-6-66	426.0
17	4-6-66	429.6
18	4-1-66	419.4
19	4-7-66	492.3
20	4-7-66	501.8
	ERATH COUNTY*	
1	3-25-66	339.1
2	4-4-66	345.7
3	3-25-66	294.8
4	3-24-66	400.9
5	12-22-66	390.4
6	3-24-66	381.9

Appendix II D, continued.

No.	Date	Water Level Elevation (m)
	Erath County, cont.	
7	3-31-66	391.6
8	11-29-66	391.4
9	3-24-66	387.7
10	3-24-66	376.8
11	3-24-66	378.5
12	8-31-66	375.7
13	3-25-66	416.9
14	3-25-66	352.4
15	3-31-66	329.9
16	3-25-66	328.6
17	2-23-66	325.5
18	3-25-66	327.9
19	3-31-66	314.4
20	4-4-66	314.8
21	2-24-66	320.0[1]
22	2-23-66	325.9
23	3-24-66	369.2
24	3-24-66	396.8
25	3-24-66	327.8
26	3-24-66	281.2
	FALLS COUNTY	
1	2-28-66	151.8
	3-16-70	136.9
	3-26-74	127.4
3	3-1-66	141.3
	3-20-70	133.5
	3-20-74	124.8
	3-18-80	106.1[1]
4	3-1-66	121.4
	4-1-70	140.4
	3-20-74	130.1
	3-18-80	117.4
5	3-1-66	149.4
	3-20-70	143.8
	3-20-74	144.8
7	3-19-70	145.7
	3-20-74	139.2
10	3-1-66	153.5
	3-20-70	149.1
	3-20-74	144.8
	3-17-80	132.3

No.	Date	Water Level Elevation (m)
39	5-5-66	155.9
	4-17-70	152.5
	3-20-74	147.5
	HAMILTON COUNTY*	
1	3-25-66	242.5
2	4-6-66	271.0
3	4-12-66	303.6
4	4-7-66	264.9
	LAMPASSAS COUNTY*	
1	3-3-66	432.8
2	3-3-66	422.9
3	3-3-66	410.8
4	2-17-66	396.1
5	2-17-66	391.3
6	3-3-66	389.7
7	3-3-66	394.3
8	3-4-66	285.6
9	3-3-66	422.7
10	3-3-66	416.5
11	2-2-66	307.2
12	3-4-66	314.9
13	3-4-66	291.7
14	3-7-66	254.9
	McLENNAN COUNTY	
4	3-2-66	126.5
	4-17-70	125.5
	3-25-74	115.8
	3-10-80	89.3
9	3-17-66	135.9
	4-7-70	126.7
	3-25-74	118.6
	3-12-80	90.2[1]
12	4-2-70	58.5
	3-27-74	46.8
	3-10-80	25.1

Appendix II D, continued.

No.	Date	Water Level Elevation (m)
	McLennan County, cont.	
19[3]	3-15-66	113.4
	3-12-70	111.0
	2-27-74	95.4
	3-13-80	72.4
21	3-1-66	136.4
	3-12-70	127.0
24	3-7-66	147.6
27	9-12-66	142.6
	3-9-70	122.9
	2-27-74	94.8
	3-11-80	92.3
29[3]	3-30-70	87.5
	3-27-74	75.0
	3-11-80	54.8
48	3-17-66	58.8
	3-3-70	58.6
	3-1-74	47.2
	3-12-80	22.2
51	3-15-66	98.5[1]
	3-3-70	129.7
54	3-12-70	93.7
	2-27-74	83.8
55	3-1-66	136.2
	3-12-70	116.9
	2-27-74	107.3
	3-13-80	79.5
66	4-7-70	103.4
	3-27-74	89.5
70	3-2-66	63.1
	2-27-70	66.9
	3-1-74	55.9
	3-10-80	27.0
75	3-28-66	94.0
	4-14-70	78.9
	3-15-74	71.2
	3-12-80	47.4
77	2-28-66	141.1
	3-18-70	130.8
	3-1-74	122.3
	3-12-80	99.2

No.	Date	Water Level Elevation (m)
83	3-15-66	119.0
	3-11-70	132.3
	2-27-74	100.2[1]
	3-13-80	92.9
86	3-1-66	129.7
	3-13-70	104.4
	3-1-74	95.1
89	2-28-66	146.4
	3-3-70	135.8
	3-25-74	126.7
92	4-2-70	69.2
	3-29-74	58.2
	3-13-80	34.1[1]
93	4-7-70	93.8
	3-27-74	79.4
94	8-26-66	92.2
	2-27-70	86.2
	2-25-74	77.5
95	8-26-66	90.0
96	3-15-66	132.9
	3-3-70	118.5
	3-25-74	106.3
	MILAM COUNTY	
1	2-21-66	162.6
	3-20-70	157.7
	3-20-74	151.8[1]
	MILLS COUNTY*	
1	4-13-66	419.8
2	4-12-66	415.7
3	4-12-66	414.7
4	4-13-66	385.1
5	4-12-66	419.8
6	4-12-66	400.8
7	4-12-66	417.8

Appendix II D, continued.

No.	Date	Water Level Elevation (m)
	WILLIAMSON COUNTY	
1	3-17-66	255.4
2	3-22-66	155.2
3	3-17-66	252.5
4	3-21-66	253.5
5	3-21-66	153.2
6	3-21-66	197.1
7	3-21-66	155.1
8	3-21-66	156.2
9	3-21-66	155.8

Appendix II D, continued: Cross-reference to wells in counties marked with an asterick (*).

BOSQUE

No.	TDWR No.
1	40-03-601
2	40-05-701
3	40-05-903
4	40-12-805

BURNET

No.	TDWR No.
1	41-63-901
2	41-64-801
3	57-15-702
4	57-16-801
5	57-23-203
6	57-24-101
7	57-24-103
8	57-24-801
9	58-01-801

COMANCHE

No.	TDWR No.
1	31-51-606
2	31-52-214
3	31-52-503
4	31-52-605
5	31-52-709
6	31-52-904
7	31-53-701
8	31-53-721
9	31-53-722
10	31-57-606
11	31-58-703
12	31-59-302
13	31-59-703
14	31-59-901
15	31-60-206
16	31-60-211
17	31-60-401
18	31-60-503
19	31-60-901
20	31-61-112
21	31-61-201
22	31-61-404
23	41-02-603
24	41-03-101
25	41-03-903
26	41-04-502
27	41-04-603
28	41-05-202
29	41-05-204
30	41-05-503
31	41-05-801
32	41-05-901
33	41-05-902
34	41-06-701
35	41-06-901
36	41-12-304
37	41-13-201
38	41-14-102
39	41-14-303
40	41-14-701
41	41-14-702
42	41-15-401

CORYELL

No.	TDWR No.
1	40-26-102
2	40-34-201
3	40-35-103
4	40-35-403
5	40-35-701
6	40-35-804
7	40-43-603
8	41-39-304

EASTLAND

No.	TDWR No.
1	30-48-201
2	30-48-701
3	30-56-407
4	30-56-202
5	30-56-510
6	31-35-604
7	31-36-702
8	31-42-505
9	31-42-806
10	31-43-702
11	31-43-803
12	31-44-401
13	31-44-502
14	31-44-802
15	31-44-804
16	31-51-211
17	31-51-215
18	31-51-306
19	31-57-108
20	31-57-429

ERATH

No.	TDWR No.
1	31-39-502
2	31-46-901
3	31-48-401
4	31-52-303
5	31-52-616
6	31-53-203
7	31-53-207
8	31-53-404
9	31-53-501
10	31-53-503
11	31-53-718
12	31-53-805
13	31-54-601
14	31-54-801
15	31-55-107
16	31-55-114
17	31-55-202
18	31-55-208
19	31-55-301
20	31-55-601
21	31-55-801
22	31-55-803
23	31-61-301
24	31-62-104
25	31-63-301
26	41-08-202

HAMILTON

No.	TDWR No.
1	40-09-201
2	41-08-301
3	41-15-501
4	41-24-401

LAMPASAS

No.	TDWR No.
1	41-45-901
2	41-45-902
3	41-53-202
4	41-53-309
5	41-53-319
6	41-53-503
7	41-54-801
8	41-56-101
9	41-61-101
10	41-62-101
11	41-63-302
12	41-63-303
13	41-63-607
14	41-64-604

MILLS

No.	TDWR No.
1	41-27-601
2	41-35-301
3	41-35-601
4	41-36-201
5	41-36-401
6	41-44-202
7	41-45-401

WILLIAMSON

No.	TDWR No.
1	58-10-702
2	58-13-503
3	58-17-802
4	58-18-701
5	58-21-202
6	58-26-705
7	58-29-602
8	58-29-603
9	58-29-604

Appendix II E: Reported bottom-hole pressures, Falls County area study.

No.	Unit	ISIP	FSIP	Middle of Production Interval (km)
			FALLS COUNTY	
12	G		864	0.559
	G		958	0.588
	H		1275*	0.872
13	G		875	0.590
	H		1365*	0.918
17	G		1950	1.223
	S		3210*	2.044
22	G		150	1.673
	G		2000	1.675
	G		2950	1.867
29	H	3956	3927*	2.673
31	S	4587	4587*	3.003
32	H	3892	3829	2.808
40	G	2544	2544	1.718
			LIMESTONE COUNTY	
20	S	3860	4170*	2.620
24	G		2540	1.977
	G		2700	2.033
	H		470	2.246
27	G		1950	1.383
28	S		3650*	2.519
45	G		2000	1.614
	H		1950	1.784
46	G		2525	1.801
48	S	3415*	3305	2.335
49	G		1900	1.283
	H		1975*	1.414
	H		0	1.929
	S		3000*	2.086
50	H		2005	1.498
52	H		3221	2.170
	S		3932*	2.648
53	H		2610	1.936
55	H	5506	5931	3.467
	H	3820	6037	3.514
61	H	2623	3393	2.561
	H	1245	1245	3.478
	H	5019	5552*	3.581
62	S	3237	4433*	3.071

Appendix II E, continued.

No.	Unit	ISIP	FSIP	Middle of Production Interval (km)
		Limestone County, cont.		
64	G		2575	2.099
	H		610	2.309
	H		1550	2.318
65	G		2750	1.882
66	H		2705	2.302
	H		3320	2.388
	H		3300	2.466
	H		1450	2.507
	H		3800*	2.551
69	H	3180	3070*	2.106
71	H		3320	2.151
	H		3340	2.186
	H		3300*	2.208
72	S	5329	5329	3.282
	S	4013	5387*	3.319
73	S		3585	3.268
74	G		85	1.220
	G		1780	1.323
76	H		4111	2.695
77	H		3395	2.062
78	H		2995*	2.048
79	H		3100	2.087
81	G		2625	1.985
	G		3250	2.049
82	H		3390*	2.245
83	S	3752	5002*	3.408
85	H		2900	2.171
86	H		2110	2.217
	H		3220	2.292
87	H		3125	2.161
	H		3250*	2.184
	H		3875	2.161
	H		3250	2.161
88	H		3270	2.166
	H		2675	2.236
89	H		3475	2.219
90	H		3750	2.343
92	H		3775	2.583

Appendix II E, continued.

No.	Unit	ISIP	FSIP	Middle of Production Interval (km)
			MILAM COUNTY	
5	H		1665*	1.172
19	H		3275*	2.284
	H		3485*	2.309
20	H		2400	2.239
	H		820	2.376
			ROBERTSON COUNTY	
16	S		6655	3.850
17	G		2200	2.032
18	H		3000	2.209
19	G		1635	1.833
	G		2515	1.860
20	H		2500	2.140
22	H		2739	2.150
23	G	2789	2789	1.935
	H	3856	3323	3.240
	H	5688	5661*	3.547
	S	3800	4348	3.888

Appendix II F: Geothermal gradients calculated from bottom-hole temperatures, Falls County area.

No.	Unit	Bottom-Hole Temp. (°C)	Geothermal Gradient (°C/km)	Depth (km)
		BELL COUNTY		
1	P	46.7	25.5	1.082
2	H	43.3	34.6	0.687
	H	43.3	32.3	0.735
7	H	42.8	32.2	0.718
9	H	43.3	36.7	0.650
10	P	43.3	58.0	0.412
11	P	37.8	36.2	0.504
12	P	48.9	42.4	0.688
24	H	46.1	32.8	0.806
28	P	40.0	33.9	0.616
29	P	54.4	66.8	0.528
	P	57.2	27.8	1.371
31	P	37.8	48.8	0.377
		FALLS COUNTY		
5	P	52.2	36.7	0.876
10	H	42.2	24.0	0.931
12	G	34.4	25.5	0.565
	H	42.8	25.9	0.877
13	P	52.2	28.5	1.133
14	H	50.0	24.5	1.223
17	S	75.6	26.5	2.091
	S	75.6	25.6	2.166
19	H	62.8	31.1	1.368
21	H	87.8	35.8	1.889
22	G	65.0	26.7	1.679
26	H	71.1	26.7	1.906
	S	86.1	29.5	2.234
28	S	96.1	26.3	2.892
29	S	93.3	25.9	2.824
31	S	105.6	27.8	3.068
32	H	87.8	24.5	2.761
	H	93.3	25.2	2.906
	S	104.4	26.7	3.159
34	S	104.4	26.4	3.190
35*	H	54.4	30.3	1.129
	H	60.0	33.5	1.184

Appendix II F, continued.

No.	Unit	Bottom-Hole Temp. (°C)	Geothermal Gradient (°C/km)	Depth (km)
		LIMESTONE COUNTY		
1	H	45.6	27.0	0.970
2	G	42.8	32.3	0.728
4	S	82.2	23.3	2.706
9	G	57.2	26.3	1.440
	H	61.1	25.2	1.655
12	S	78.9	31.6	1.878
13	H	55.6	26.3	1.373
14	H	79.4	36.4	1.649
15	G	62.8	27.9	1.559
	S	96.1	27.4	2.807
17	H	62.2	24.3	1.765
19	H	76.7	23.5	2.440
20	S	90.6	25.8	2.755
21	H	93.3	29.6	2.494
	S	117.8	28.5	3.450
22	H	75.6	25.1	2.232
23	H	76.7	25.7	2.227
24	H	83.3	27.7	2.311
25	S	137.8	28.9	4.097
26	H	98.9	27.2	2.919
	S	147.8	29.5	4.350
27	S	81.1	25.8	2.371
28	S	81.1	23.9	2.555
29	H	81.1	26.9	2.285
30	G	75.0	28.1	1.980
31	H	62.2	21.1	2.006
32	S	110.0	27.3	3.295
33	G	72.2	25.5	2.084
35	H	80.0	27.9	2.173
36	S	101.7	24.1	3.418
37	S	107.8	25.7	3.440
38	H	105.6	27.0	3.192
39	H'	61.1	23.0	1.800
	H	68.9	25.9	1.898
40	S	123.9	27.0	3.872
41	S	79.4	22.3	2.696
44	H	114.4	26.4	3.602
53	H	73.9	26.3	2.070
56	G	60.0	27.3	1.489
	H	86.7	28.2	2.391
	S	126.7	27.9	3.851
59	H	82.2	25.1	2.512
69	H	94.4	28.9	2.596

Appendix II F, continued.

No.	Unit	Bottom-Hole Temp. (°C)	Geothermal Gradient (°C/km)	Depth (km)
		Limestone County, cont.		
83	H	86.7	29.0	2.306
	S	121.1	28.6	3.551
95	S	120.0	26.8	3.749
96	H	98.9	32.3	2.462
97	S	125.6	28.1	3.770
98	H	80.0	27.2	2.222
99	H	120.6	28.1	3.597
100	H	110.0	29.6	3.043
101	S	114.4	26.1	3.615
102	H	87.8	29.4	2.319
103	S	146.7	33.4	3.790
		McLENNAN COUNTY		
3	H	49.4	43.4	0.690
4	H	39.4	23.0	0.872
6	P	46.1	36.8	0.719
8	P	52.2	27.1	1.212
9	P	43.3	25.1	0.952
13	H	46.7	41.9	0.633
14	H	43.3	26.8	0.869
21	H	46.1	33.6	0.772
22	G	42.8	64.3	0.354
23	P	42.2	47.3	0.472
46	H	46.1	37.1	0.707
50	H	43.3	26.2	0.899
51	H	48.9	32.3	0.902
	H	50.0	31.2	0.969
56	H	43.3	27.1	0.860
61	P	37.8	28.8	0.638
63	P	73.9	24.6	2.177
	P	75.6	24.0	2.305
64	P	37.8	35.9	0.488
85	H	37.8	39.8	0.451
88	H	54.4	32.2	1.066
89	P'	46.1	25.9	1.029
91	H	60.0	39.0	1.025

Appendix II F, continued.

No.	Unit	Bottom-Hole Temp. (°C)	Geothermal Gradient (°C/km)	Depth (km)
		MILAM COUNTY		
1	H	54.4	32.8	1.051
2	G	51.1	29.6	1.046
3	P	85.6	30.7	2.130
4	P	60.0	28.9	1.387
5	H'	57.2	31.8	1.167
	H	63.3	29.5	1.469
	P	68.3	30.4	1.588
9	G	62.2	24.6	1.712
	H	78.9	28.7	2.044
	P	90.0	23.5	2.975
	P	111.7	26.4	3.471
	P	127.8	28.1	3.836
10	H'	90.6	25.6	2.747
	P	133.3	31.8	3.557
	P	133.9	29.9	3.798
	P	146.1	30.2	4.168
	P	155.0	29.8	4.570
	P	155.6	29.4	4.608
14	H	48.9	24.9	1.166
		ROBERTSON COUNTY		
1	S	93.3	24.8	2.952
2	S	98.9	26.9	2.918
3	G	63.9	21.7	2.039
	H	82.2	26.0	2.382
	H	90.0	28.4	2.452
4	H	98.9	27.4	2.871
	S	192.2	32.0	5.384
5	S	122.2	27.5	3.714
	S	140.6	29.3	4.108
6	S	130.0	27.9	3.942
7	S	147.8	29.3	4.354
	S	166.7	32.4	4.522
8	S	153.9	29.7	4.502
14	G	72.2	26.1	1.997
	H	80.0	26.4	2.266
	S	176.7	34.0	4.600
15	H	93.3	29.2	2.504
17	H'	80.0	25.7	2.337

Appendix II G: Geothermal gradient calculated from produced-water temperature, Falls County area study, Hosston/Cotton Valley hydrogeologic unit.

No.	Water Temp. (°C)	Geothermal Gradient (°C/km)	Middle of Production Interval (km)
		BELL COUNTY	
2	39.4	28.2	0.704
7	35.0	22.0	0.697
8	35.6	30.3	0.531
10	29.5	26.6	0.378
14	37.2	33.4	0.529
15	30.0	28.3	0.377
16	26.7	22.9	0.320
17	46.8	29.3	0.919
21	46.7	27.9*	0.964*
22	52.8	33.7	0.977
23	23.9	14.0	0.322
27	36.7	24.6	0.694
37	25.6	17.8	0.345
40	24.4	15.3	0.333
43	27.2	31.4	0.251
44	27.2	32.7	0.241
45	27.2	30.3	0.260
46	27.2	31.8	0.248
51	35.0	24.0	0.645
55	35.0	23.5	0.658
56	36.2	31.4	0.532
		FALLS COUNTY	
1	50.6	28.6	1.064
3	34.4	18.3	0.781
4	37.0	22.2	0.764
5	46.1	30.3	0.861
7	50.6	36.7	0.834
10	43.3	25.6	0.917
35	68.9	42.6	1.142
36	32.0	14.4*	0.825*
37	51.7	30.5	1.030
38	50.0	29.1*	1.021*
41	67.2	43.9	1.074
43	61.0	36.4	1.123
44	48.0	30.5	0.915

Appendix II G, continued.

No.	Water Temp. (°C)	Geothermal Gradient (°C/km)	Middle of Production Interval (km)
		McLENNAN COUNTY	
4	35.0	18.6	0.841
9	53.5	37.3	0.912
12	33.3	20.9	0.643
19	33.3	32.2	0.414
21	40.0	24.6*	0.774*
23	36.0	37.8	0.430
25	26.7	19.0	0.351
28	30.0	27.3*	0.366*
29	34.4	34.9	0.413
37	40.0	30.8	0.667
38	45.6	37.1*	0.705*
43	45.8	38.6	0.671
50	54.4	41.4	0.837
56	55.0	43.2	0.809
57	54.4	37.1	0.927
77	62.5	40.6	1.043
81	23.9	6.6	0.559
82	47.0	34.8*	0.792*
83	34.5	34.1	0.432
86	43.0	31.4	0.727
92	41.1	32.6*	0.647*
93	41.1	36.8	0.590
94	26.0	14.6	0.397
99	46.7	32.6*	0.810*
106	37.2	36.3*	0.477*
		MILAM COUNTY	
1	54.0	33.8	1.005

APPENDIX III:

Sediment "Profiles" from Cuttings and Core Examination

The following sediment "profiles" were constructed following microscopic examination of cuttings and cores in the study area. All but three of the well samples are from the Bureau of Economic Geology Well Sample Library; samples from Falls County nos. 12 and 13 and Limestone County no. 66 were on loan from Exxon Company, U.S.A.

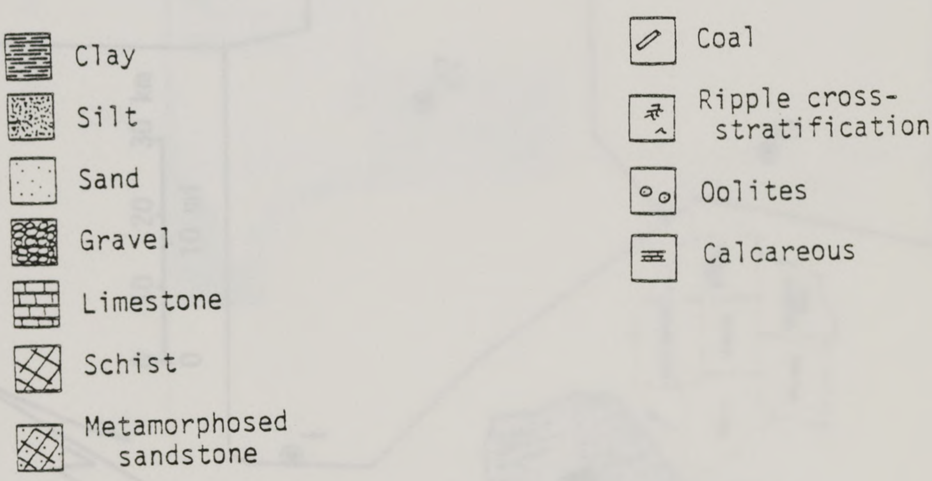
The profiles shown on the following sediment logs are grain-size profiles, and reflect the size grain which was most abundant in each interval. The tripartite division indicated for sand points to the location of fine-, medium-, and coarse-grained sand (from left to right) according to the Udden-Wentworth grain-size classification. Clay refers to clay-sized grains and does not describe mineral composition.

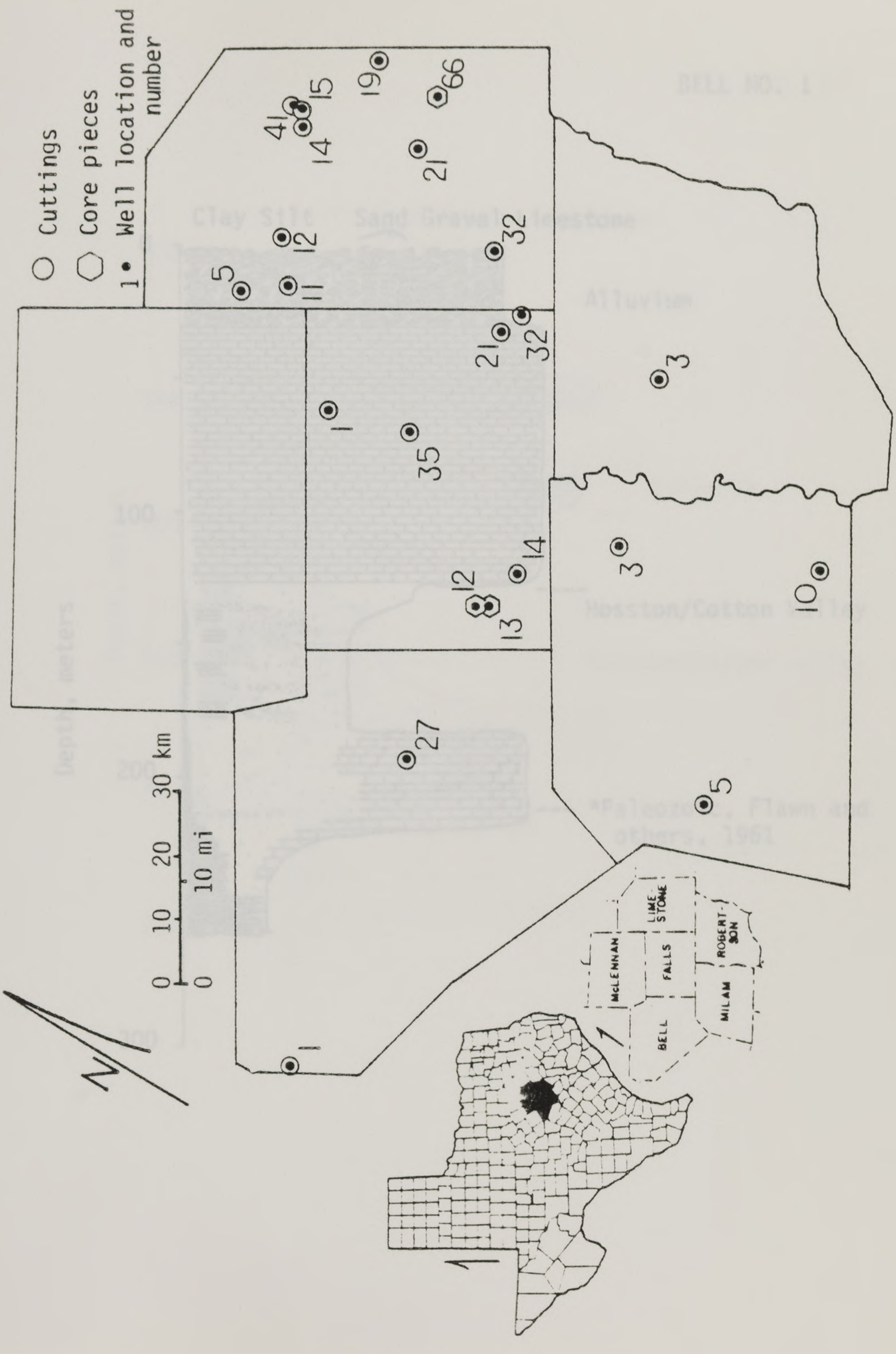
Sampling intervals for the well cuttings ranges from less than 1.5 m to more than 12 m; a core a few centimeters long may represent up to 6 m of the section. Because of this, these profiles are only generalizations of actual sediment sequences and relationships, and formation boundaries are only generally identified.

Sand was predominately well-rounded to rounded quartz. Gravel-size sediment was inferred from angular, concoidally-fractured pieces of chert, except in Falls County well no. 13 where angular pieces of red schist constituted the basal gravel in the Hosston/ Cotton Valley unit.

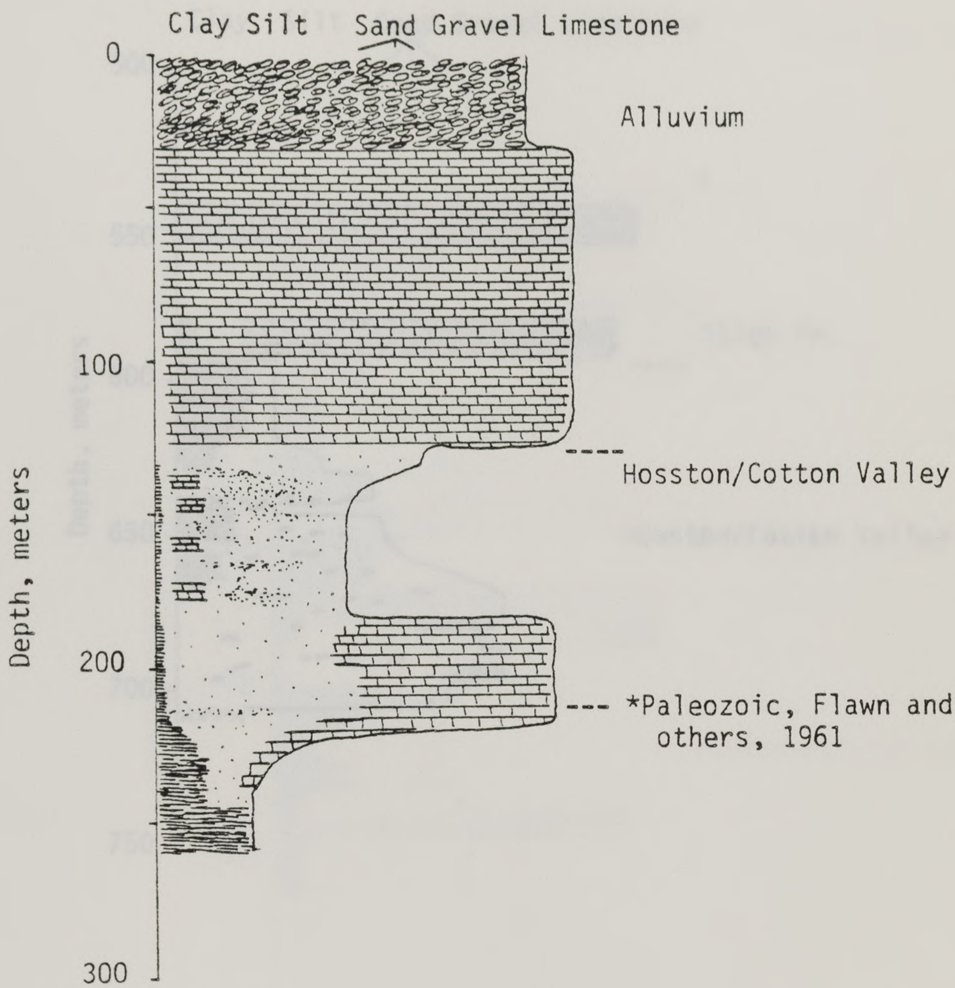
The legend below applies to all sediment logs; locations of wells which were logged is shown on the page following this introduction. Logs are arranged alphabetically by county and numerically within each county.

LEGEND

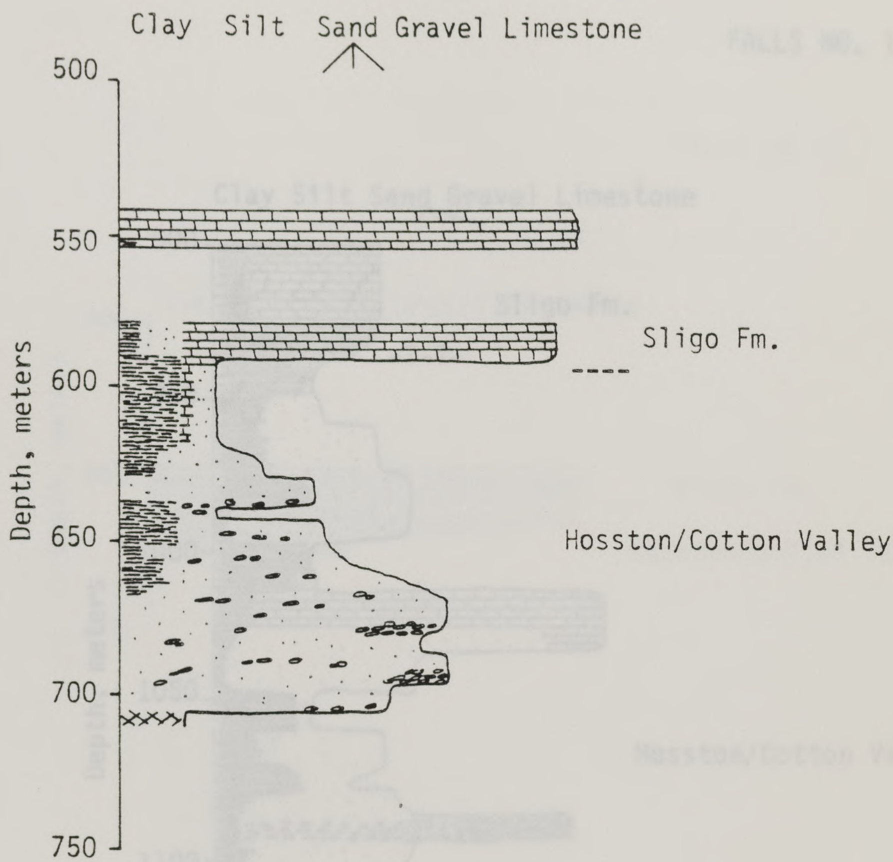



Cuttings
Core pieces
1 • Well location and number
0 10 20 30 km
0 10 mi
McLENNAN
LIME-STONE
FALLS
ROBERT-SON
BELL
MILAM

BELL NO. 1

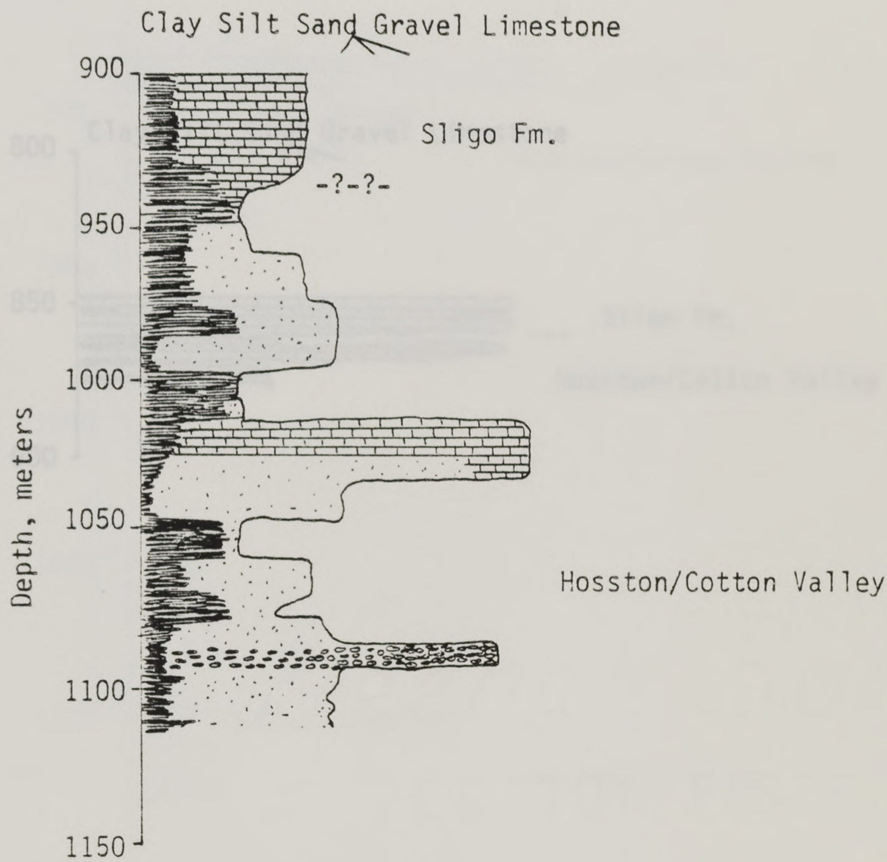

Clay Silt Sand Gravel Limestone
0
100
200
300
Depth, meters
Alluvium
Hosston/Cotton Valley
*Paleozoic, Flawn and others, 1961

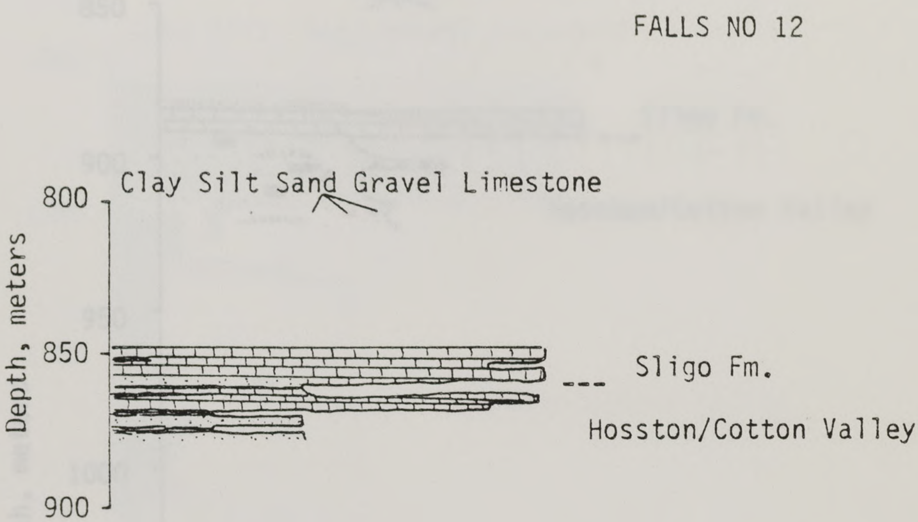
BELL NO. 27



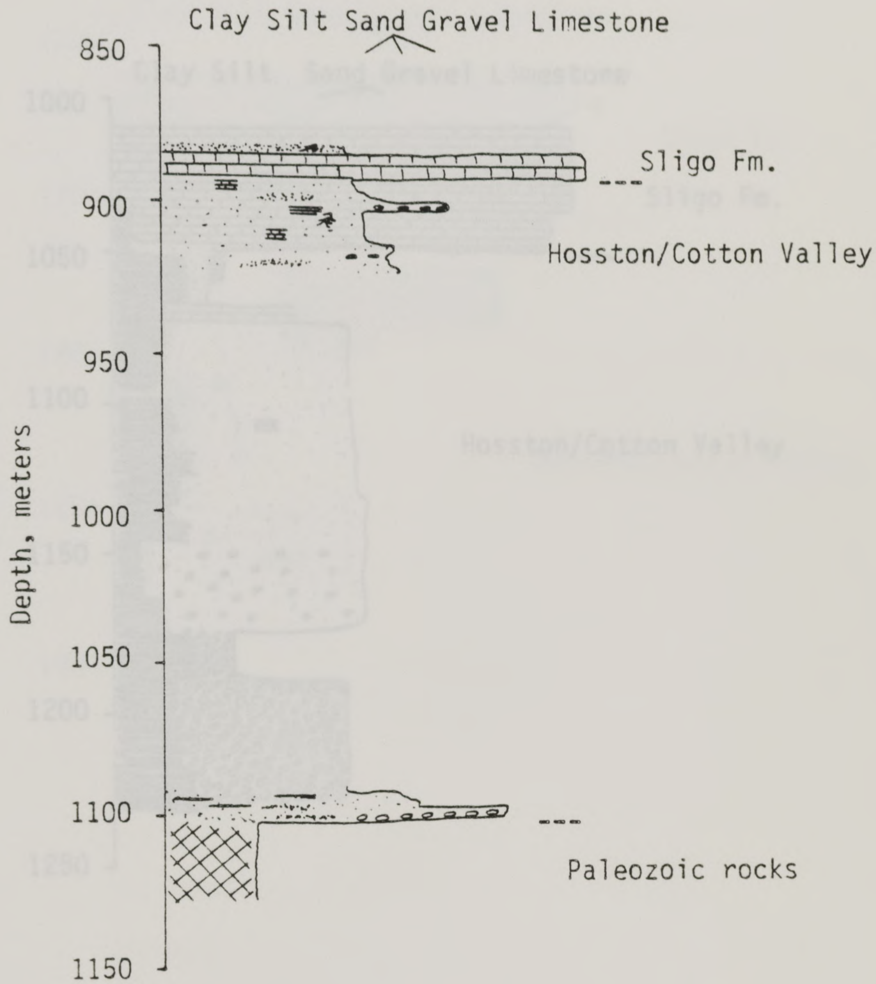
Clay Silt Sand Gravel Limestone
500
550
600
650
700
750
Depth, meters
Sligo Fm.
Hosston/Cotton Valley

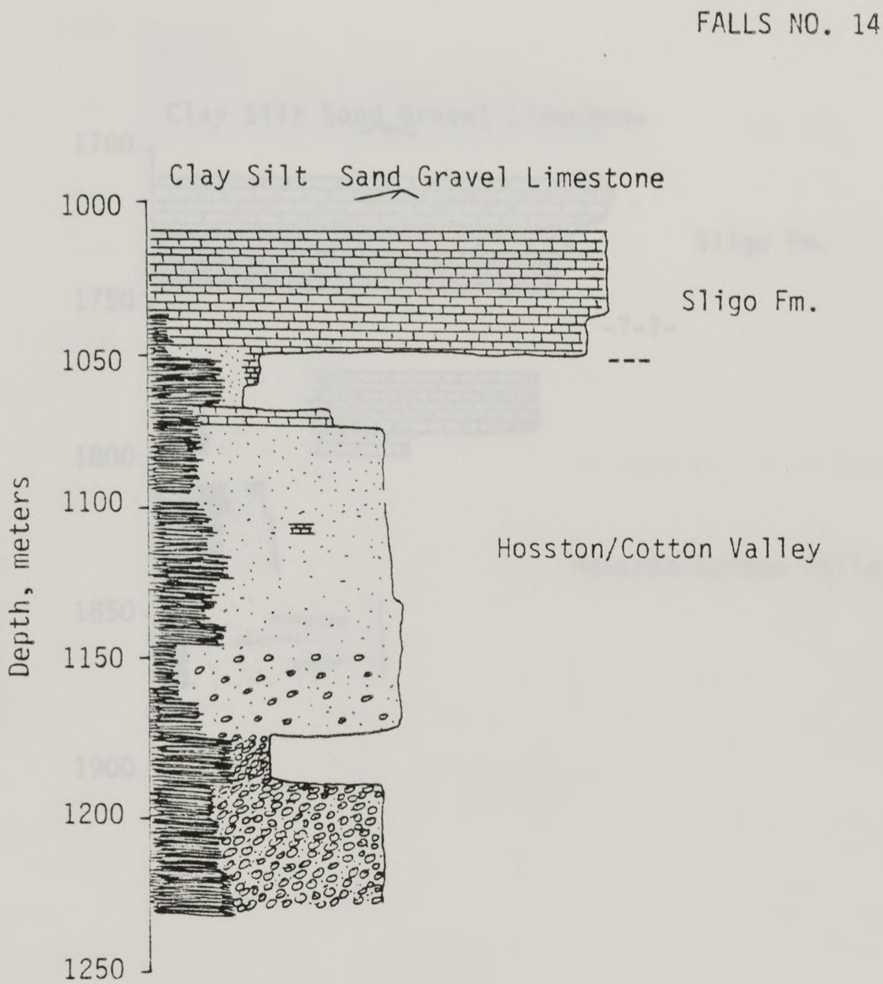
FALLS NO. 1

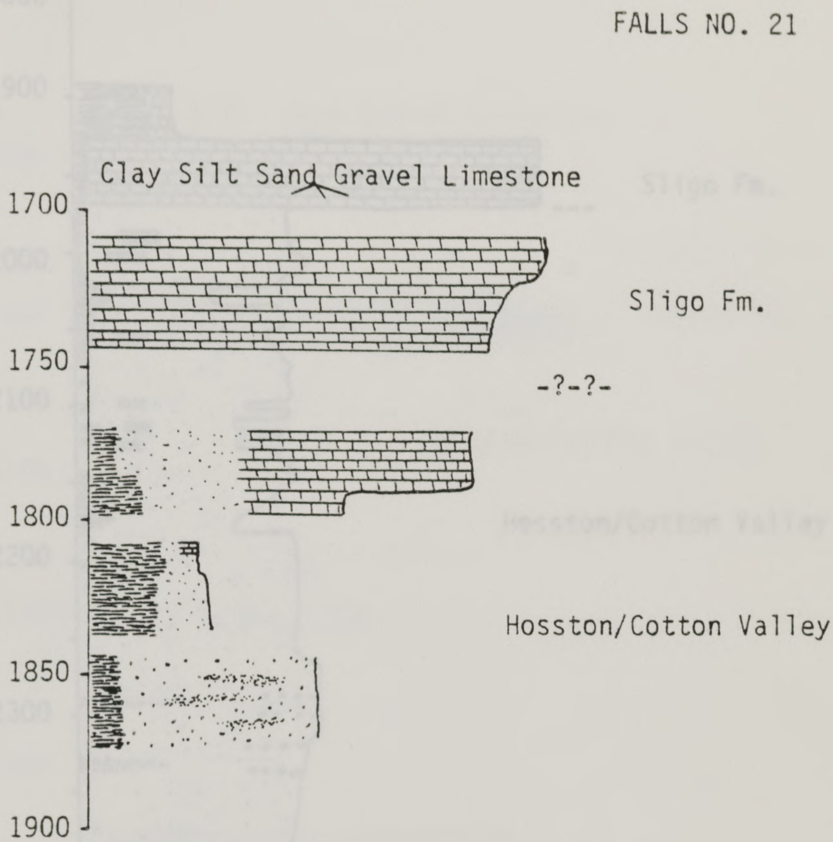

Clay Silt Sand Gravel Limestone
900
950
1000
1050
1100
1150
Depth, meters
Sligo Fm.
-?-?-
Hosston/Cotton Valley

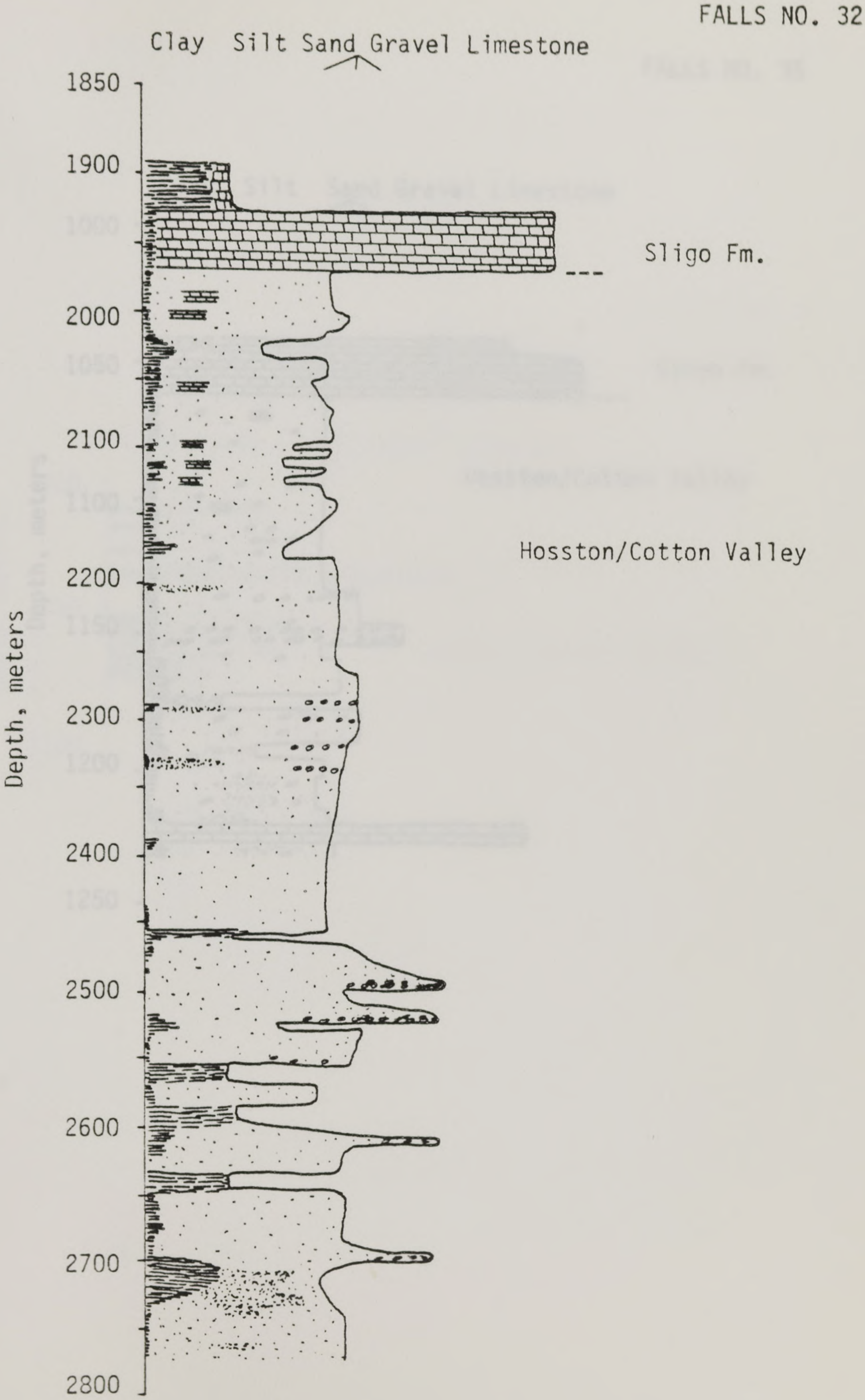

FALLS NO 12
Clay Silt Sand Gravel Limestone
800
850
900
Depth, meters
Sligo Fm.
Hosston/Cotton Valley

FALLS NO. 13

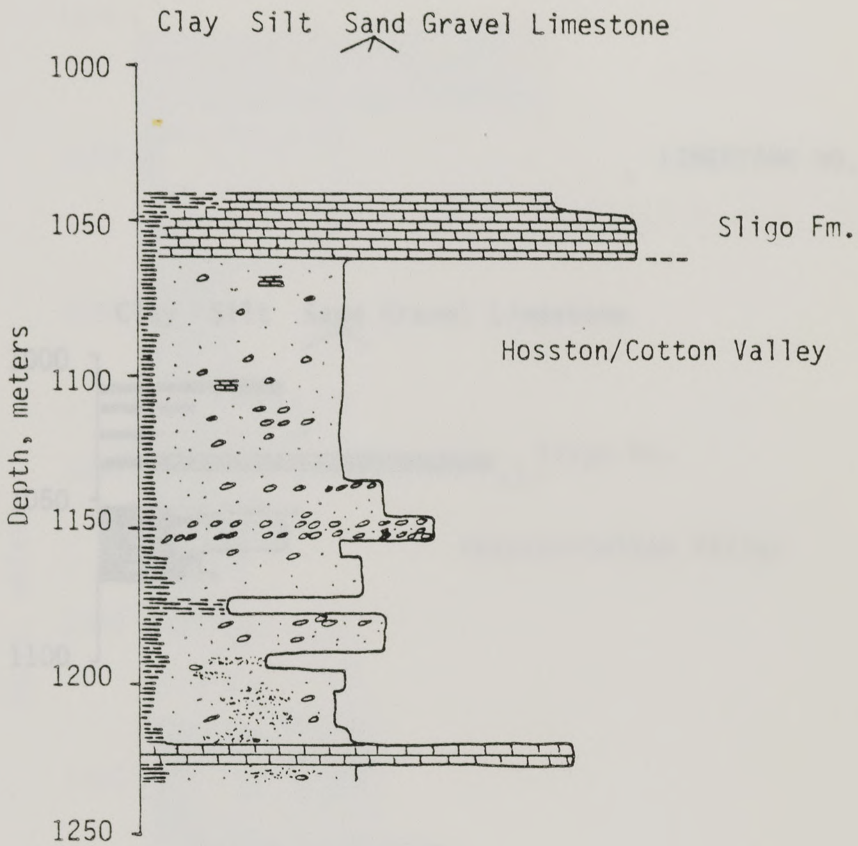

Clay Silt Sand Gravel Limestone
850
900
950
1000
1050
1100
1150
Depth, meters
Sligo Fm.
Hosston/Cotton Valley
Paleozoic rocks


FALLS NO. 14
Clay Silt Sand Gravel Limestone
1000
1050
1100
1150
1200
1250
Depth, meters
Sligo Fm.
Hosston/Cotton Valley

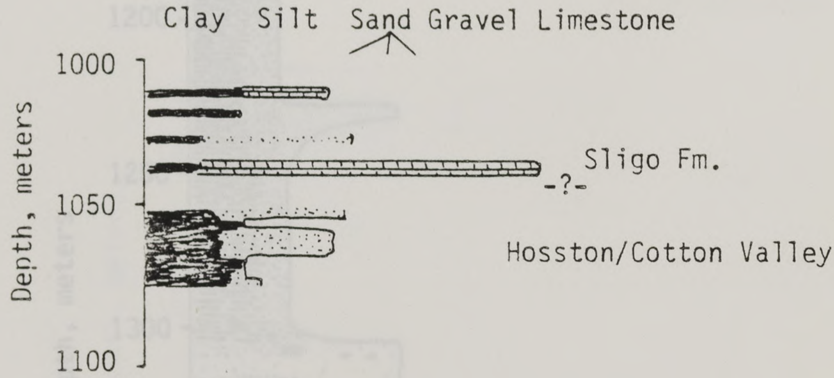

FALLS NO. 21
Clay Silt Sand Gravel Limestone
1700
1750
1800
1850
1900
Sligo Fm.
-?-?-
Hosston/Cotton Valley


FALLS NO. 32
Clay Silt Sand Gravel Limestone
1850
1900
2000
2100
2200
2300
2400
2500
2600
2700
2800
Depth, meters
Sligo Fm.
Hosston/Cotton Valley

FALLS NO. 35


Clay Silt Sand Gravel Limestone
1000
1050
1100
1150
1200
1250
Depth, meters
Sligo Fm.
Hosston/Cotton Valley

LIMESTONE NO. 5



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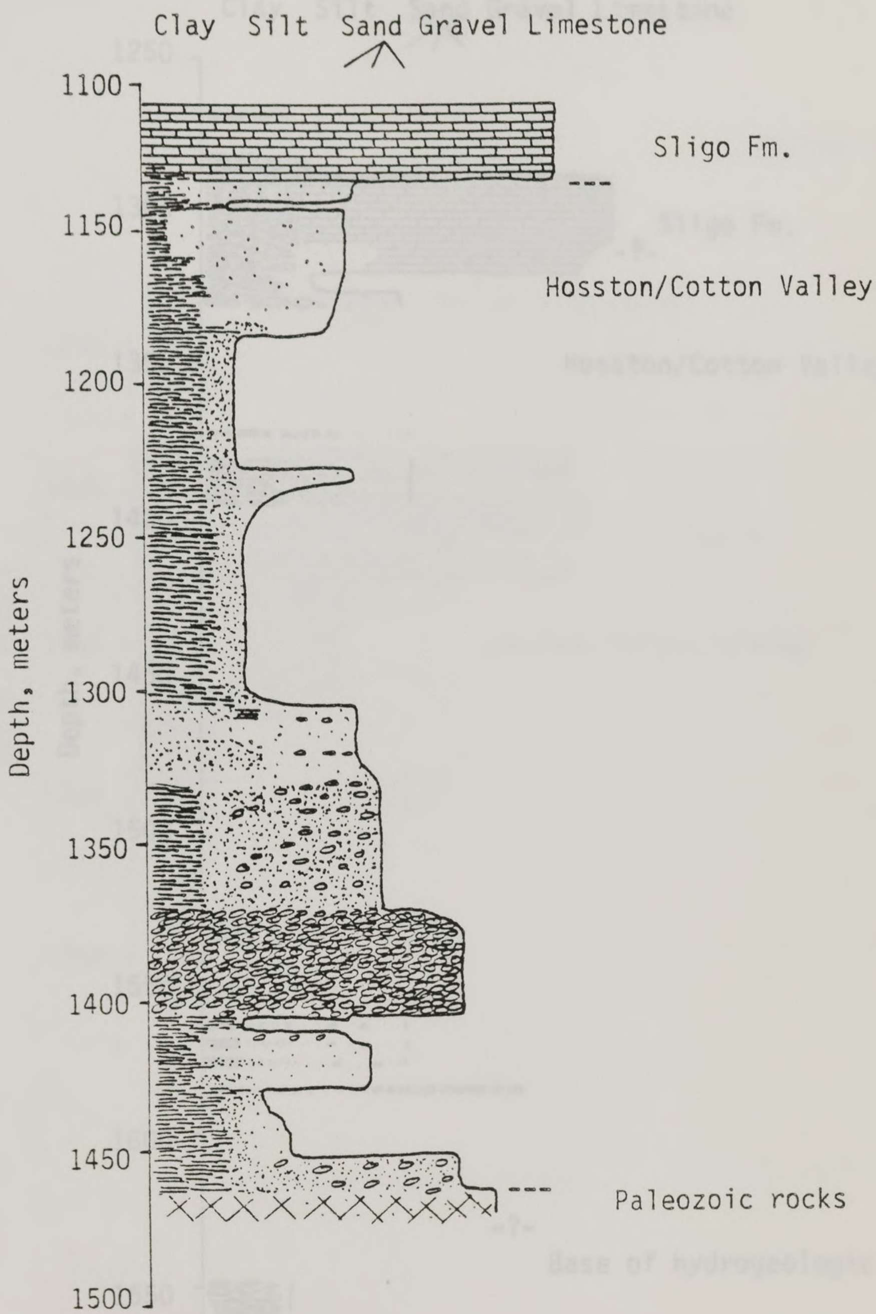

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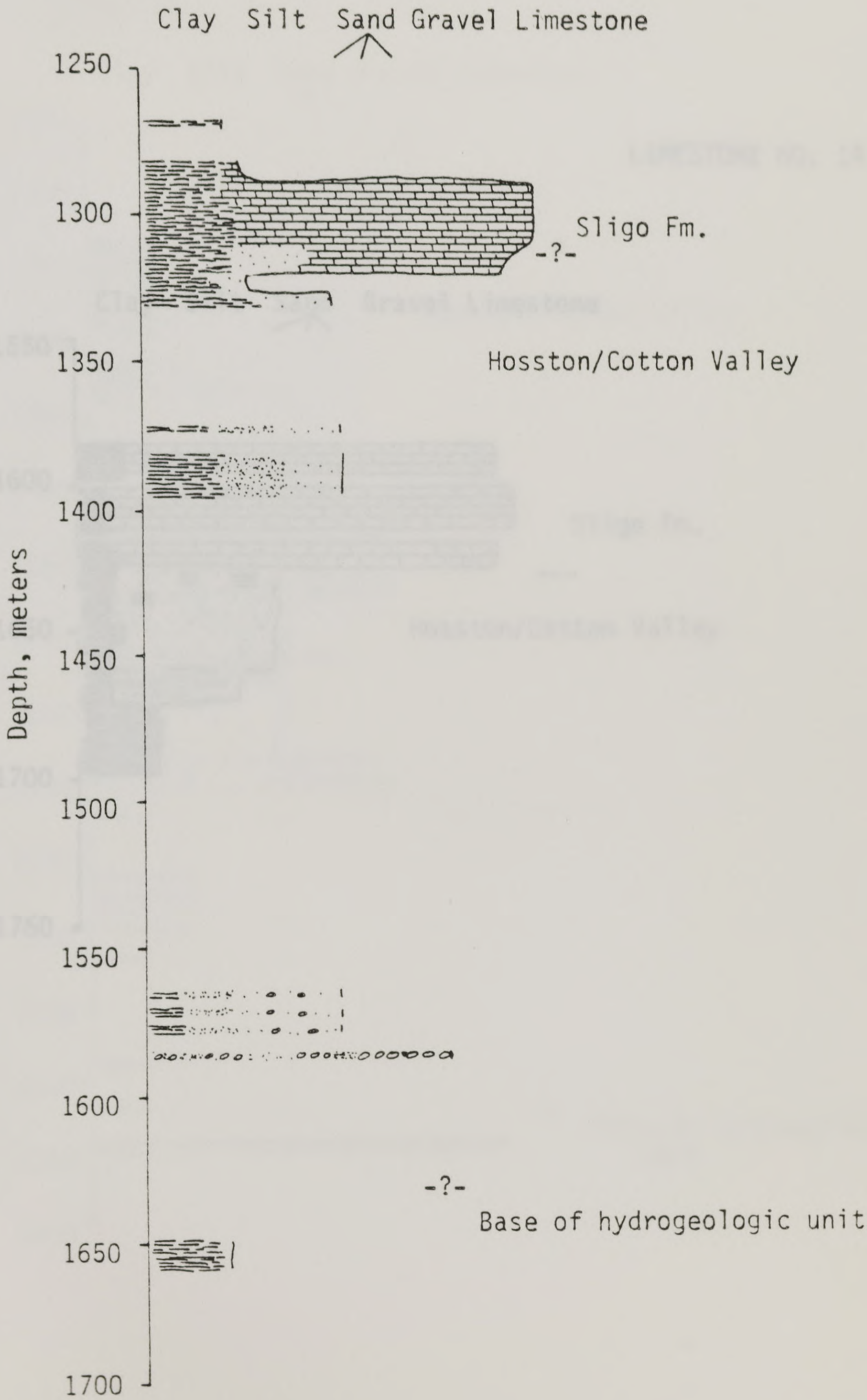

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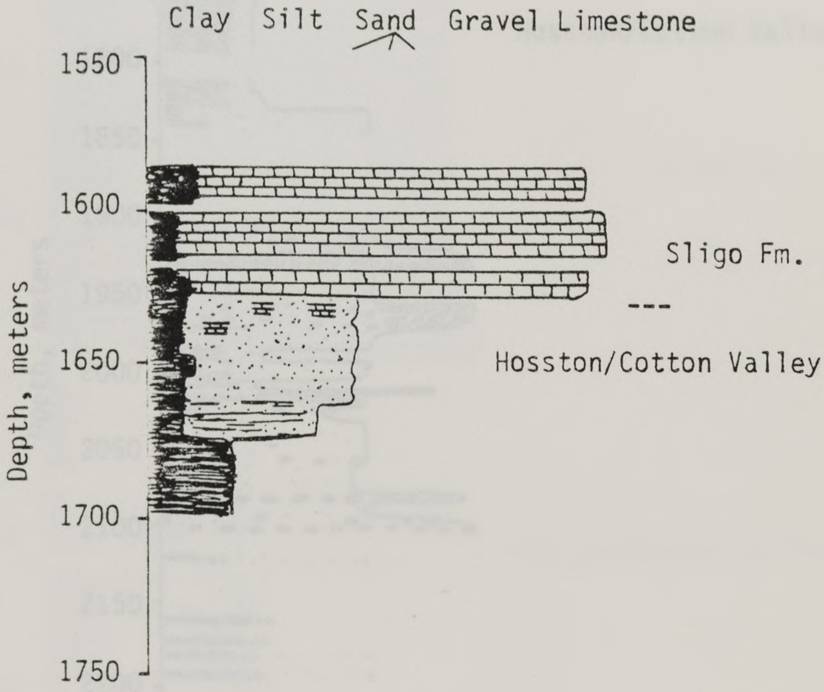

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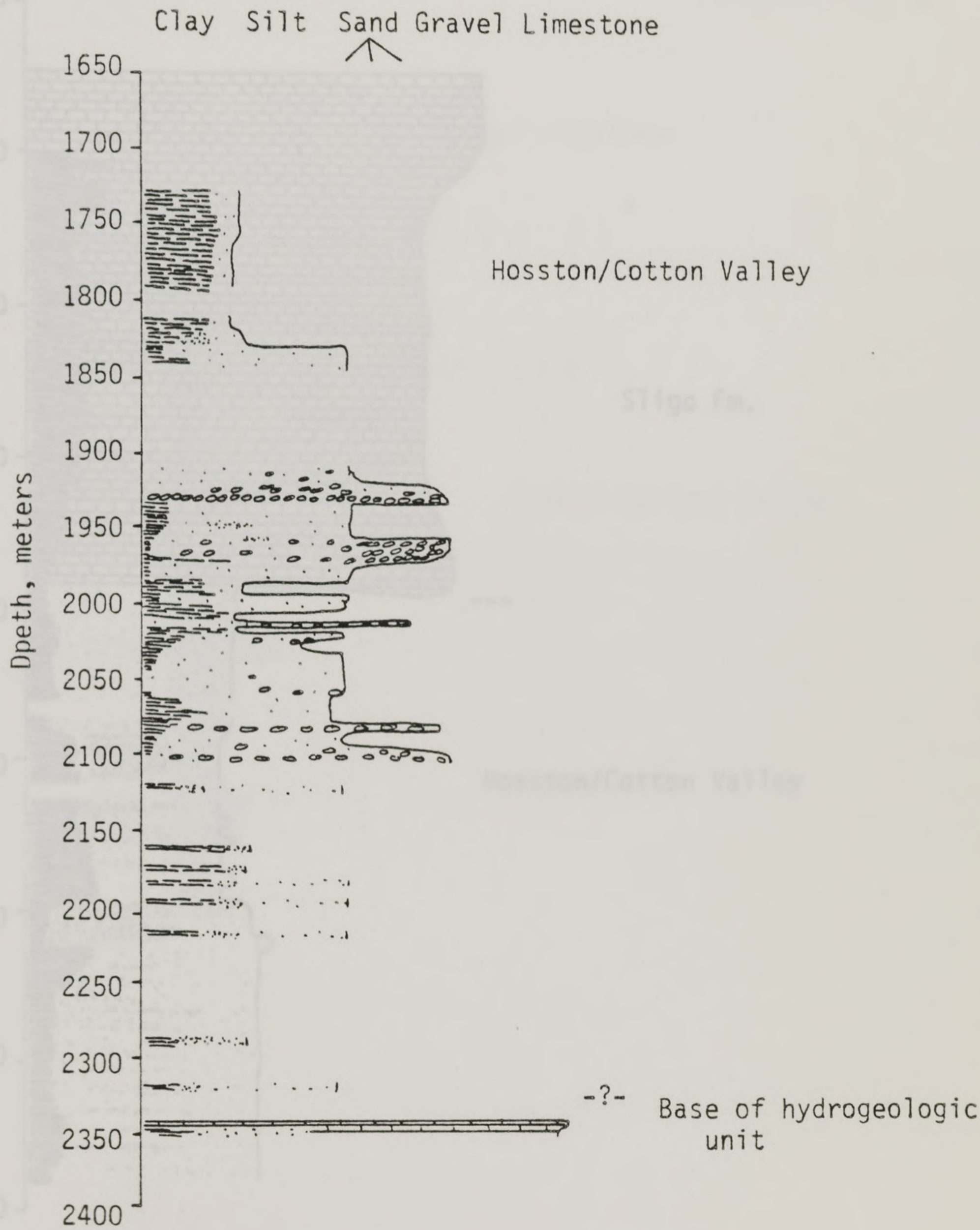

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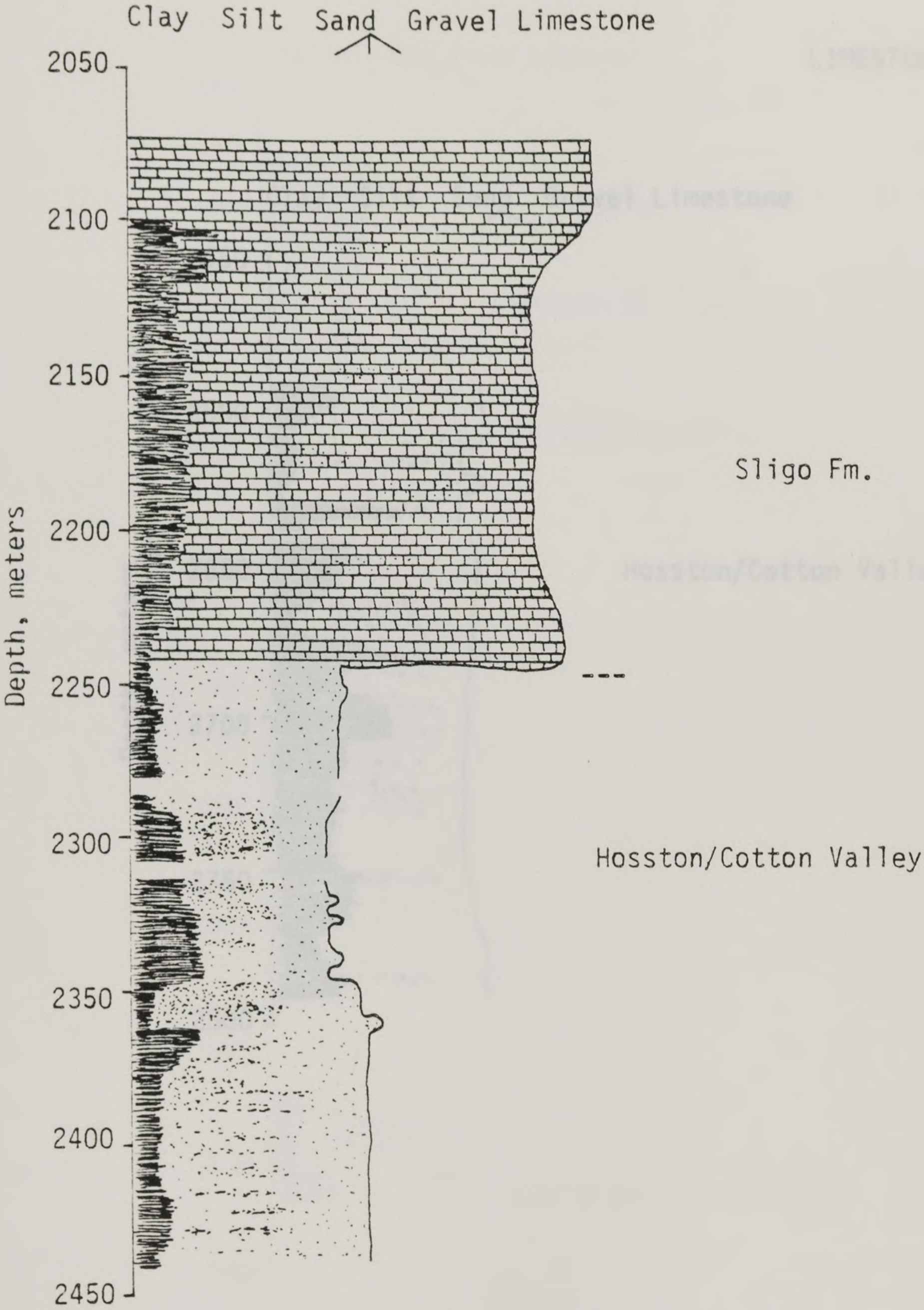

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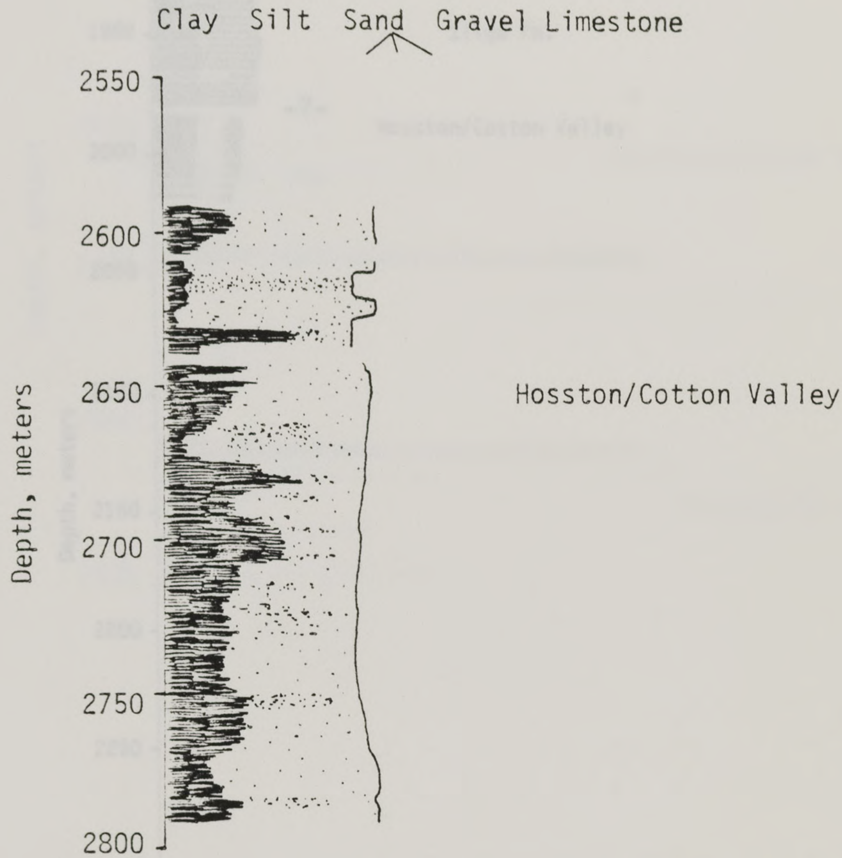

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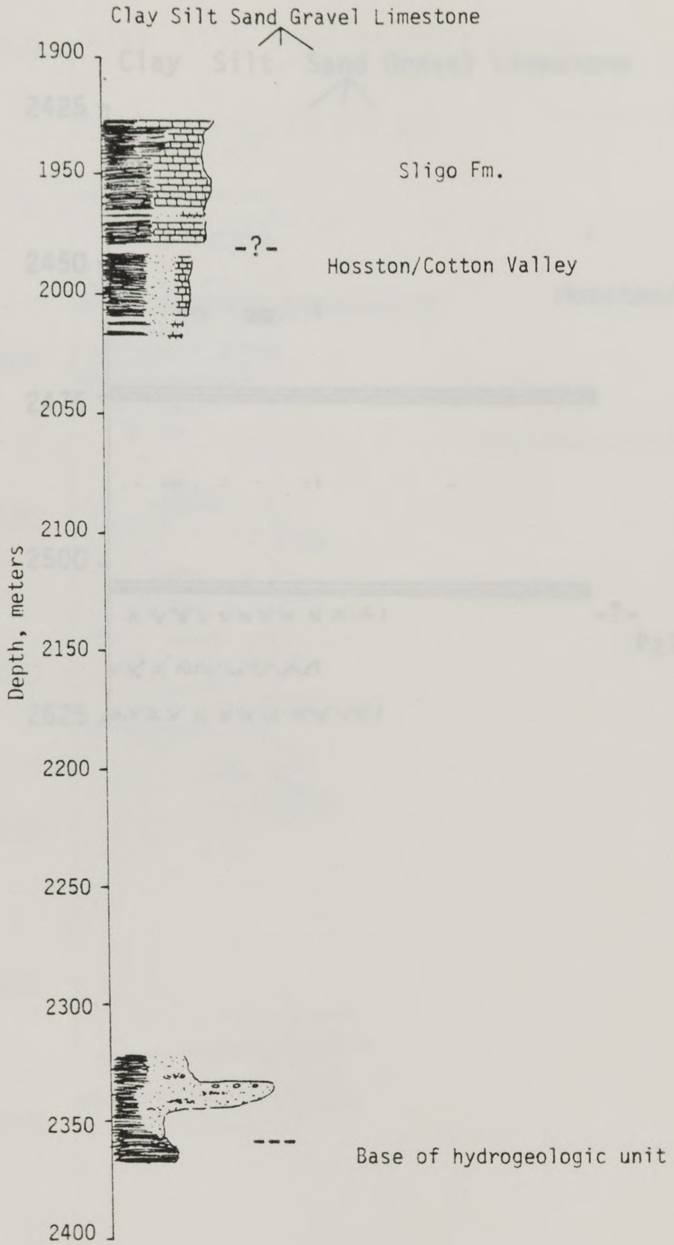
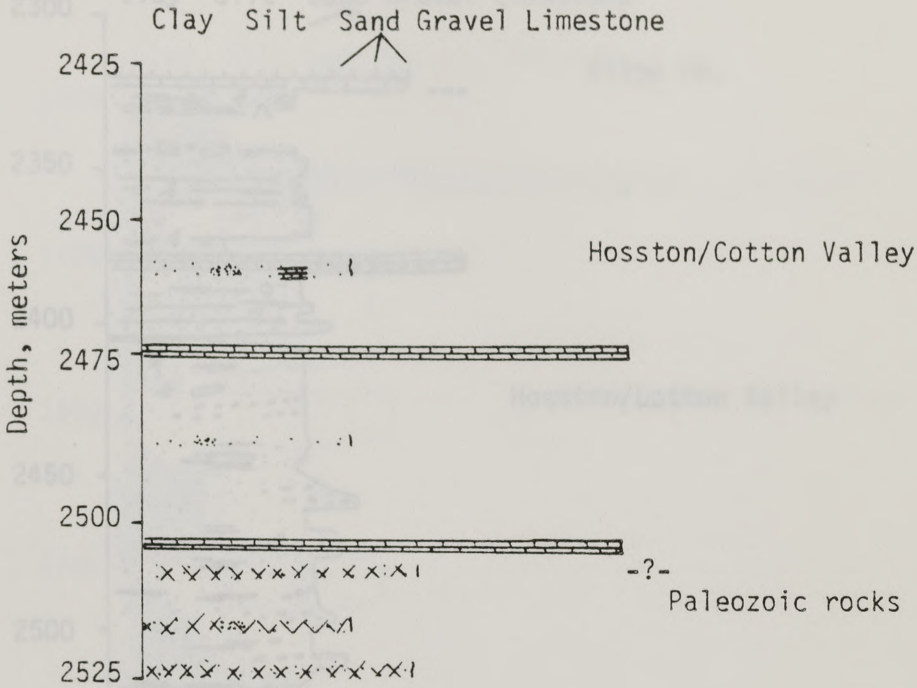
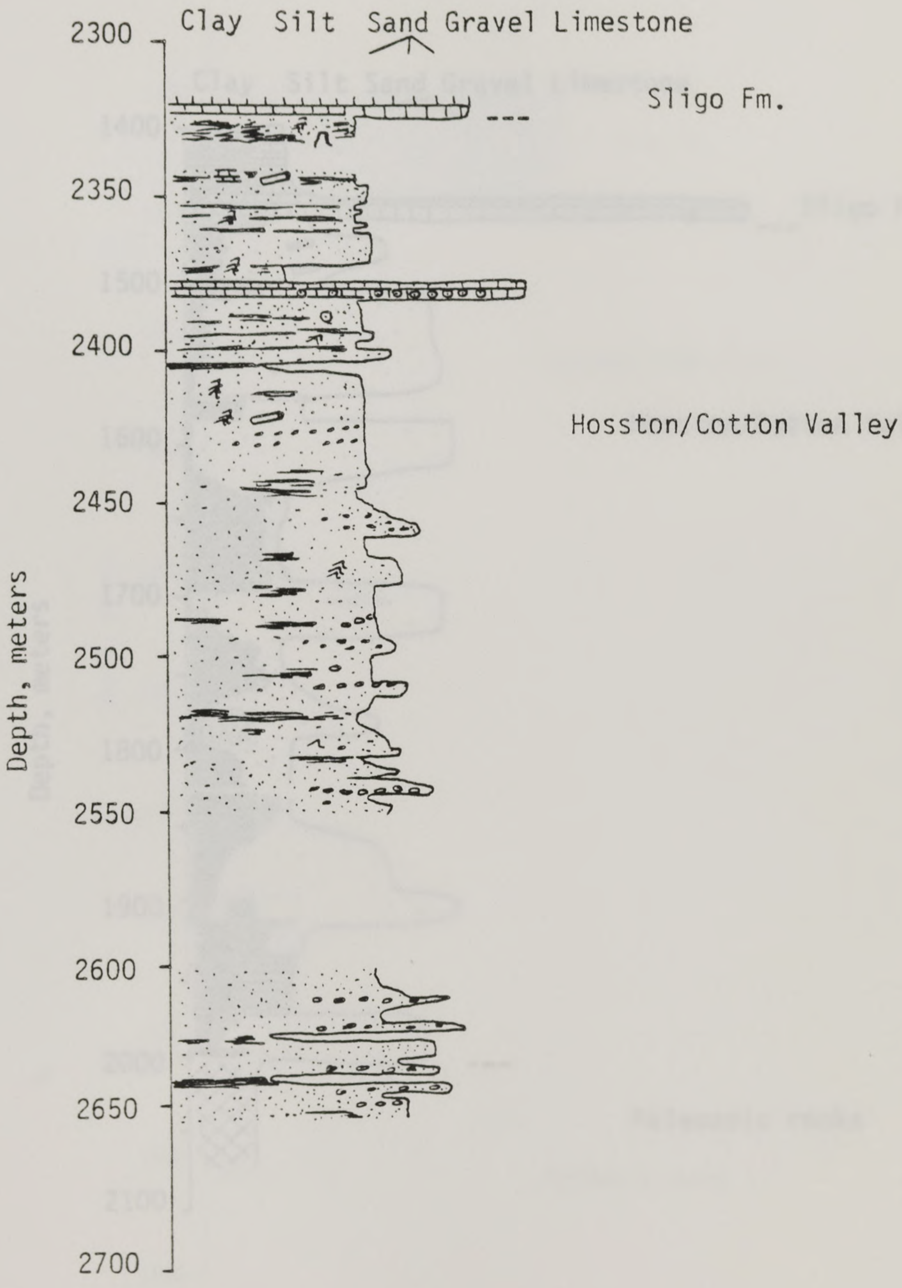
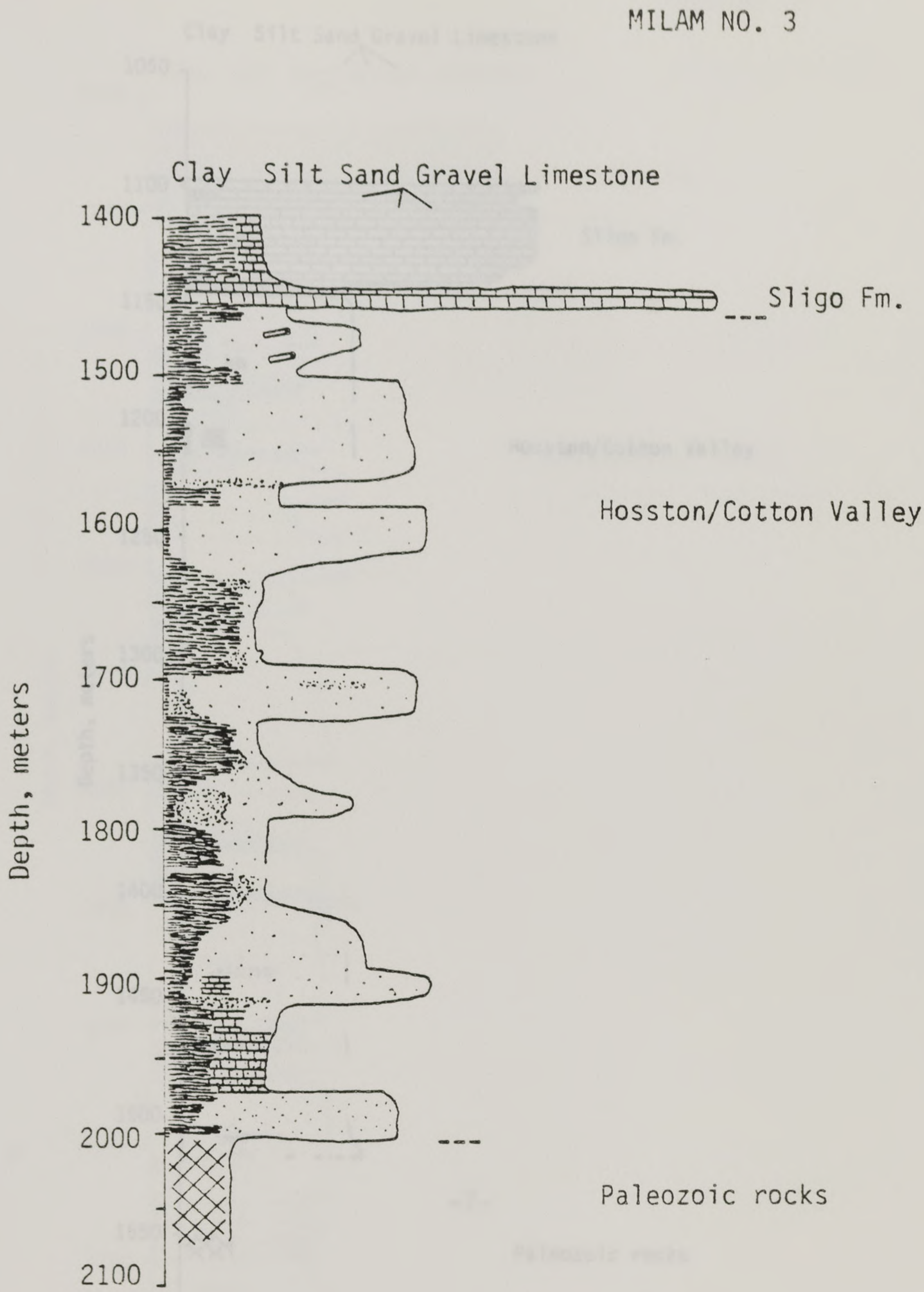


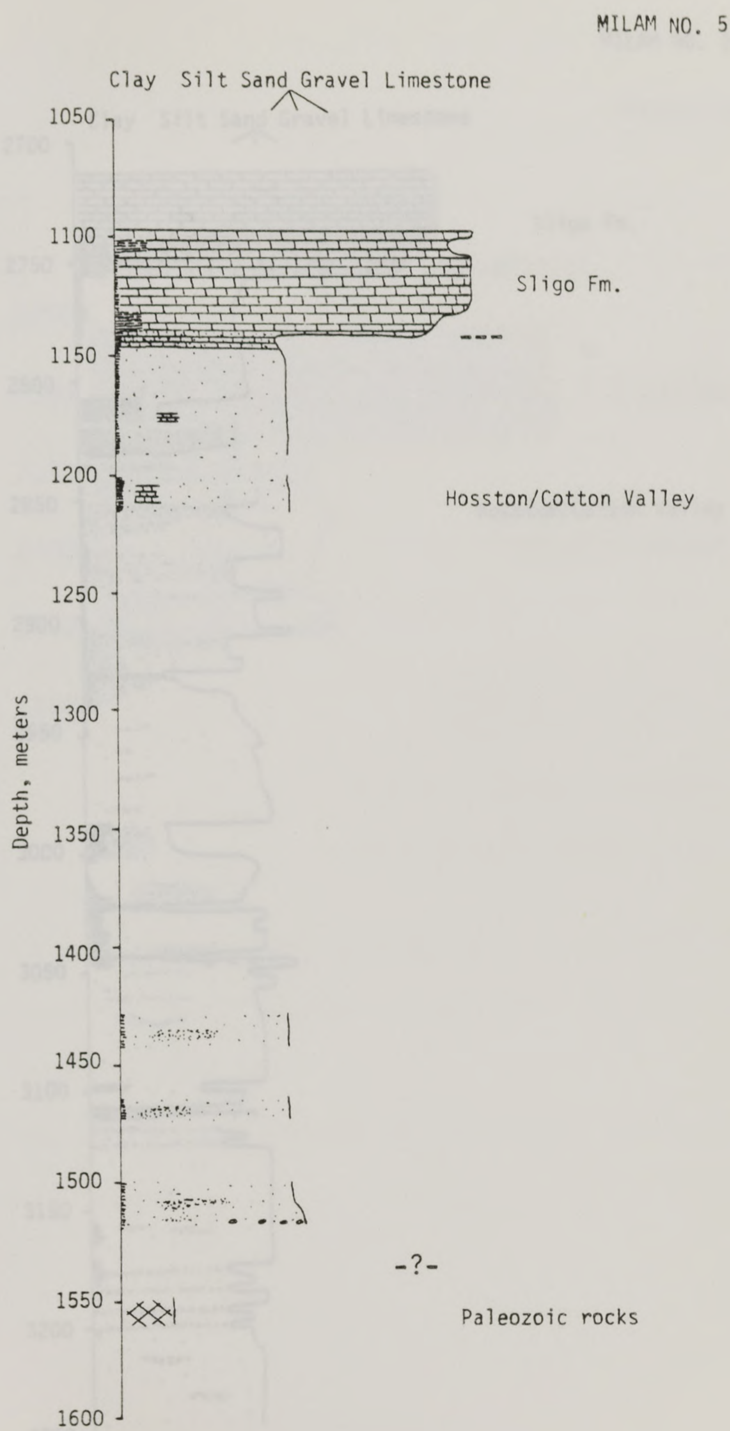
LIMESTONE NO. 41



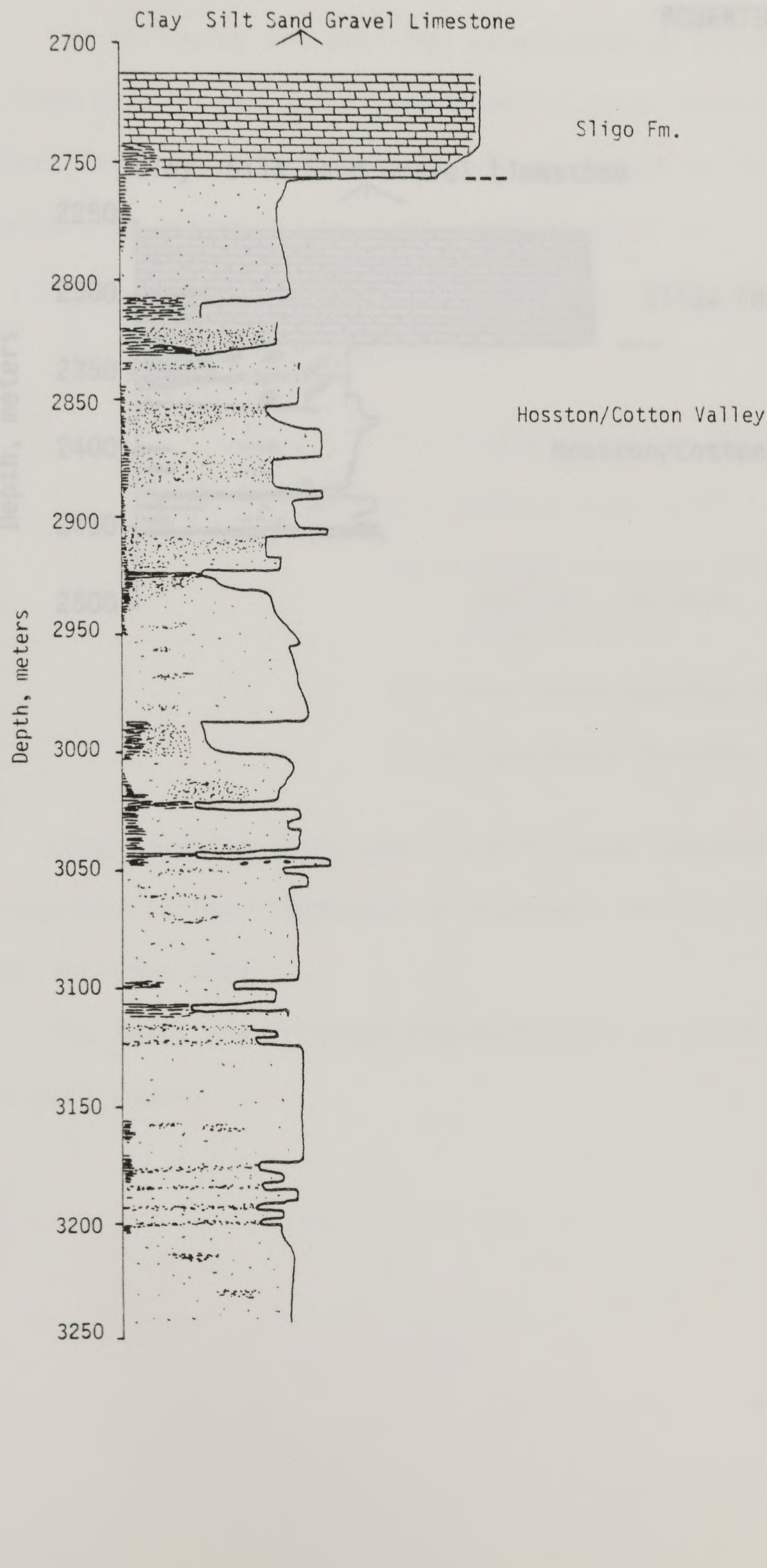
LIMESTONE NO. 66



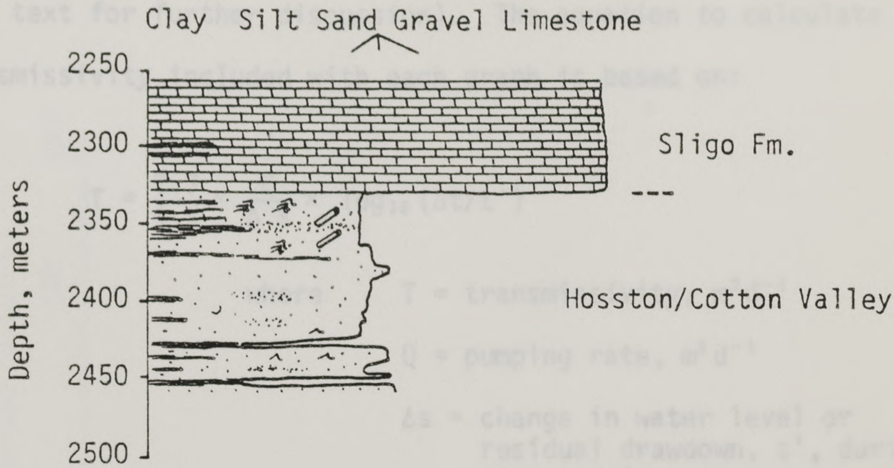

MILAM NO. 3
Clay
Silt
Sand
Gravel
Limestone
1400
1500
1600
1700
1800
1900
2000
2100
Depth, meters
Sligo Fm.
Hosston/Cotton Valley
Paleozoic rocks


MILAM NO. 5
Clay Silt Sand Gravel Limestone
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
1550
1600
Depth, meters
Sligo Fm.
Hosston/Cotton Valley
-?-
Paleozoic rocks

MILAM NO. 10


Clay
Silt
Sand
Gravel
Limestone
Depth, meters
2700
2750
2800
2850
2900
2950
3000
3050
3100
3150
3200
3250
Sligo Fm.
Hosston/Cotton Valley

ROBERTSON NO. 3



APPENDIX IV:

Pumping Test Plots

The following are semi-log (Jacob-method) plots of pumping tests from data in the Texas Department of Water Resources files (see text for further discussion). The equation to calculate transmissivity included with each graph is based on:

$$T = \frac{2.3}{4\pi} \times \frac{Q}{\Delta s} \times \log_{10}(\Delta t/t')$$

where T = transmissivity, $m^2 d^{-1}$

Q = pumping rate, $m^3 d^{-1}$

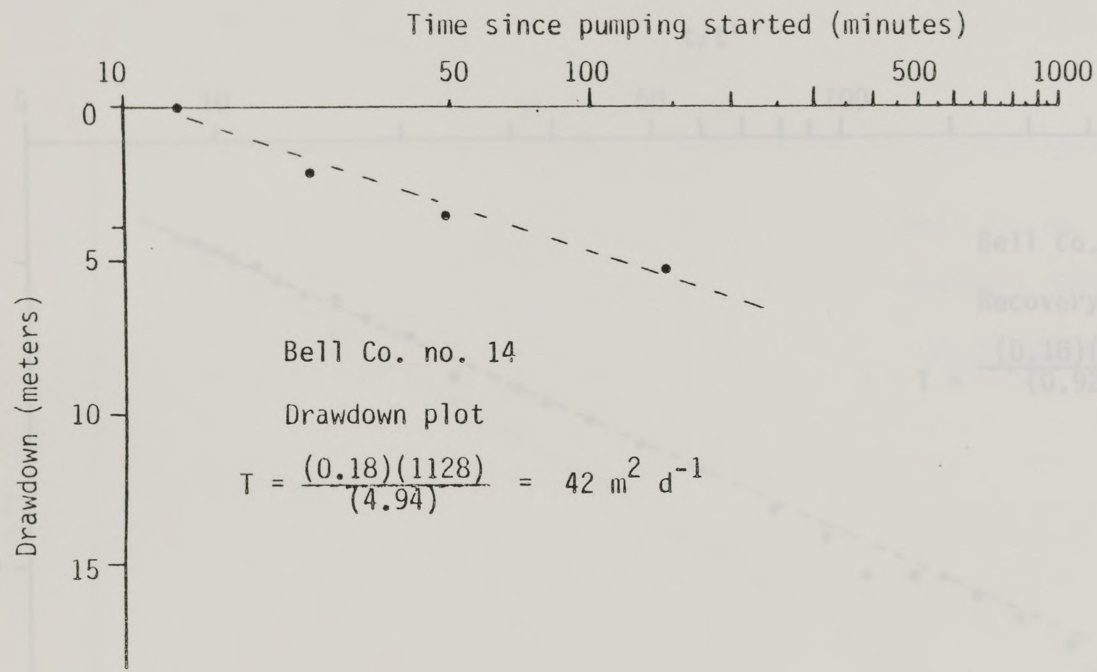
Δs = change in water level or residual drawdown, s', during time $\Delta t/t'$; m

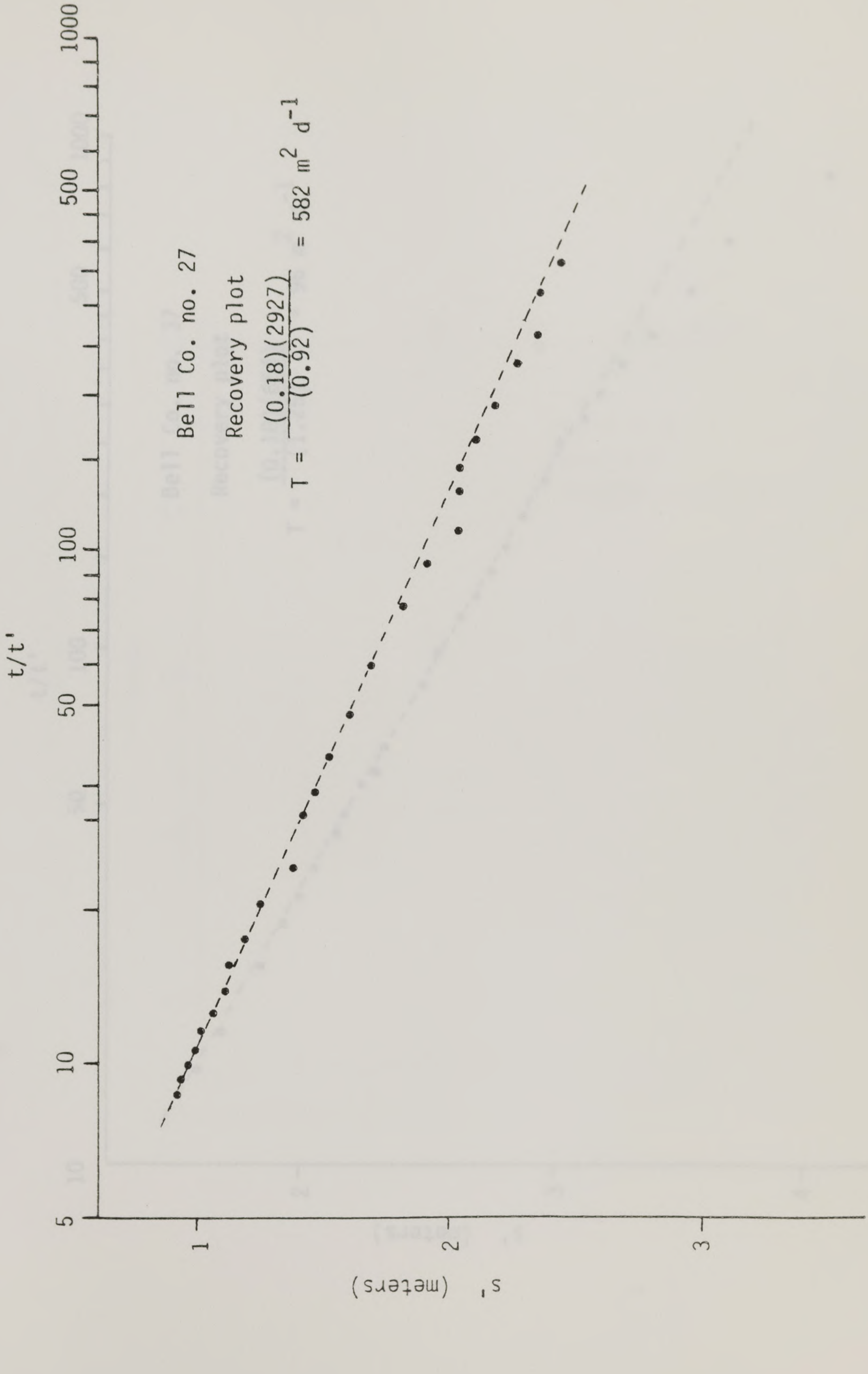
t = time since pumping started, min

t' = time since recovery started, min

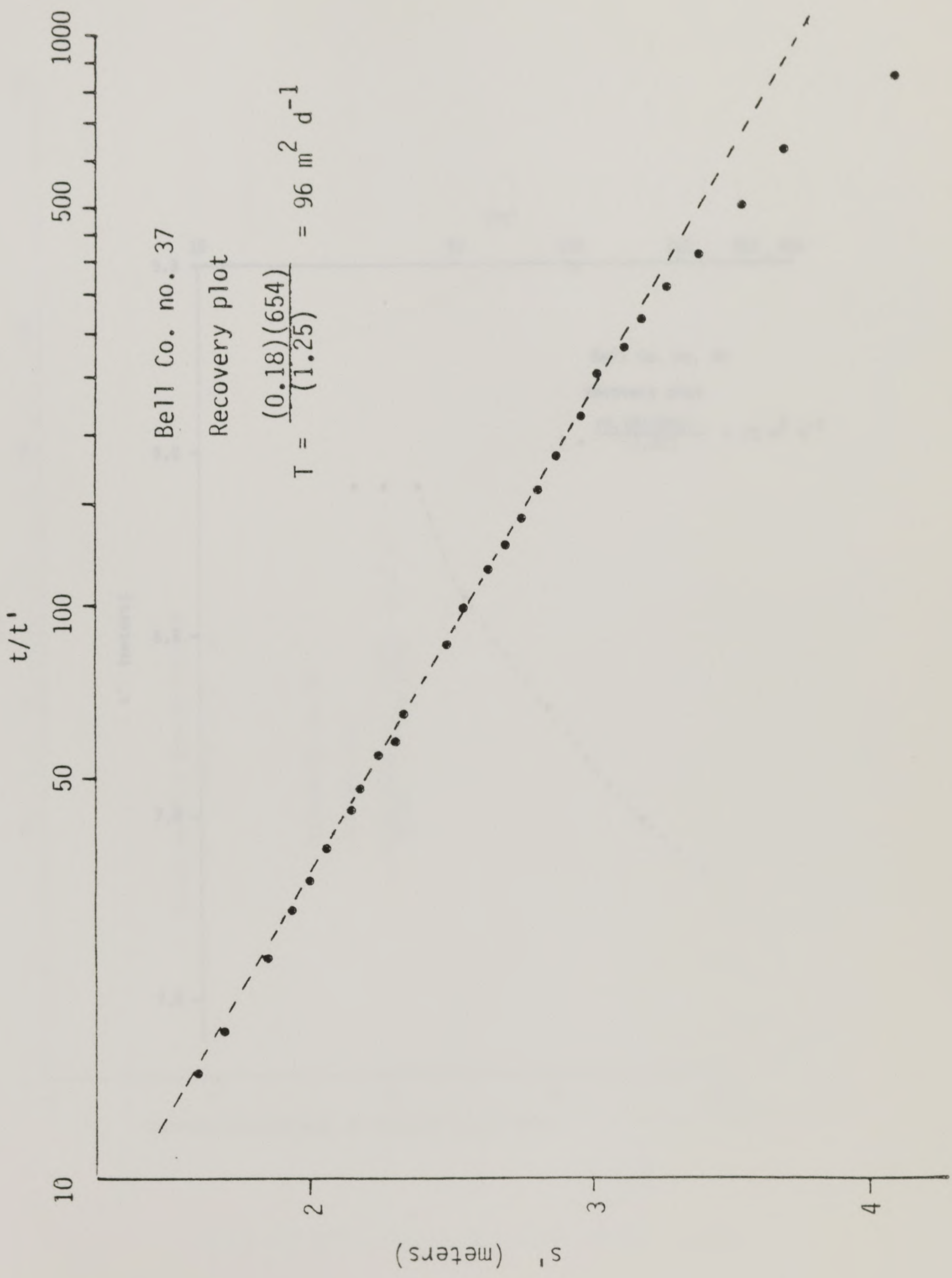
Other pumping tests used in this study (Appendix IIE) have been reported in the literature or elsewhere in this report and so are not included here.

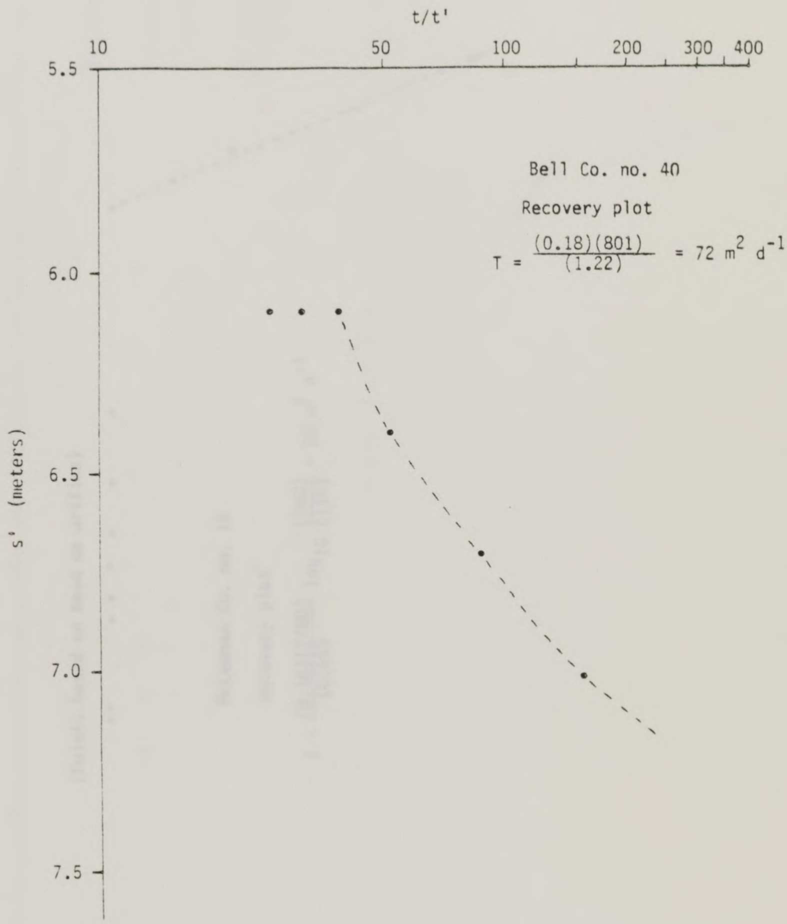
The tests are arranged alphabetically by county and numerically within each county.

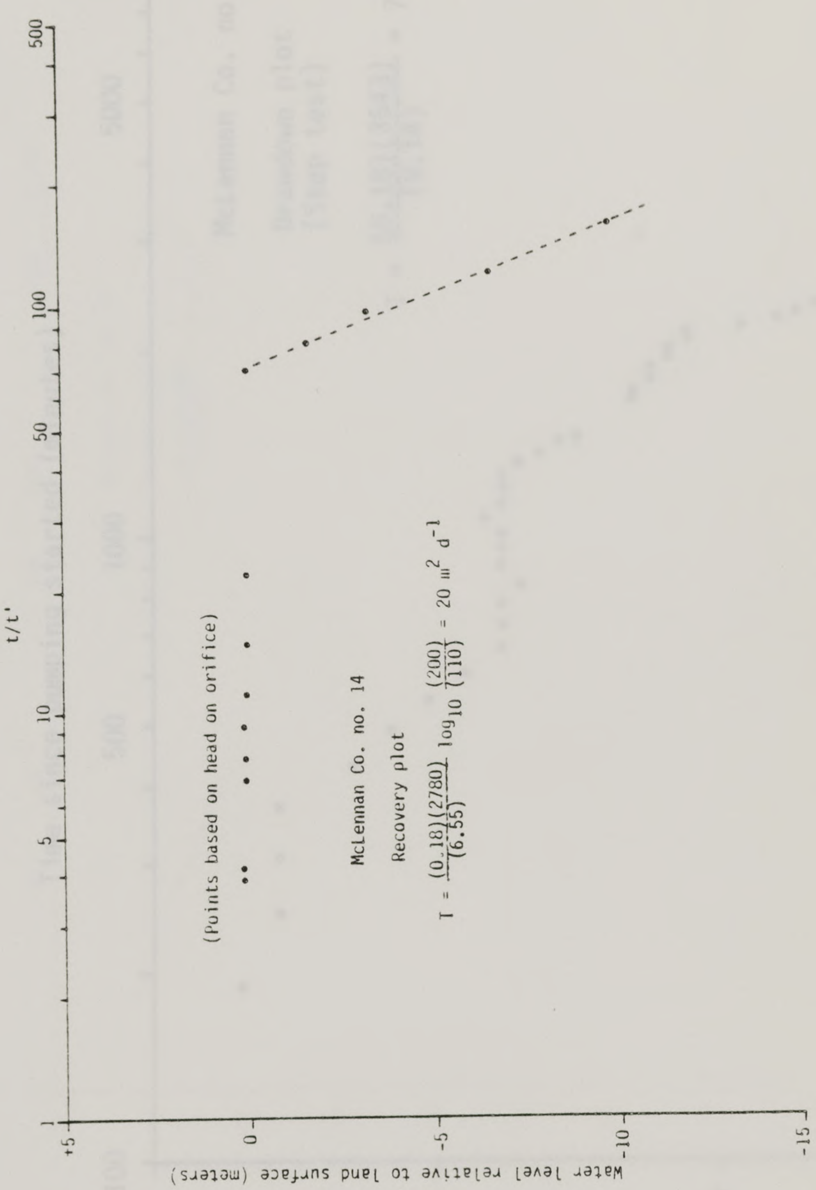

Time since pumping started (minutes)
10
50
100
500
1000
0
5
10
15
Drawdown (meters)
Bell Co. no. 14
Drawdown plot
T = (0.18)(1128) / (4.94) = 42 m2 d-1

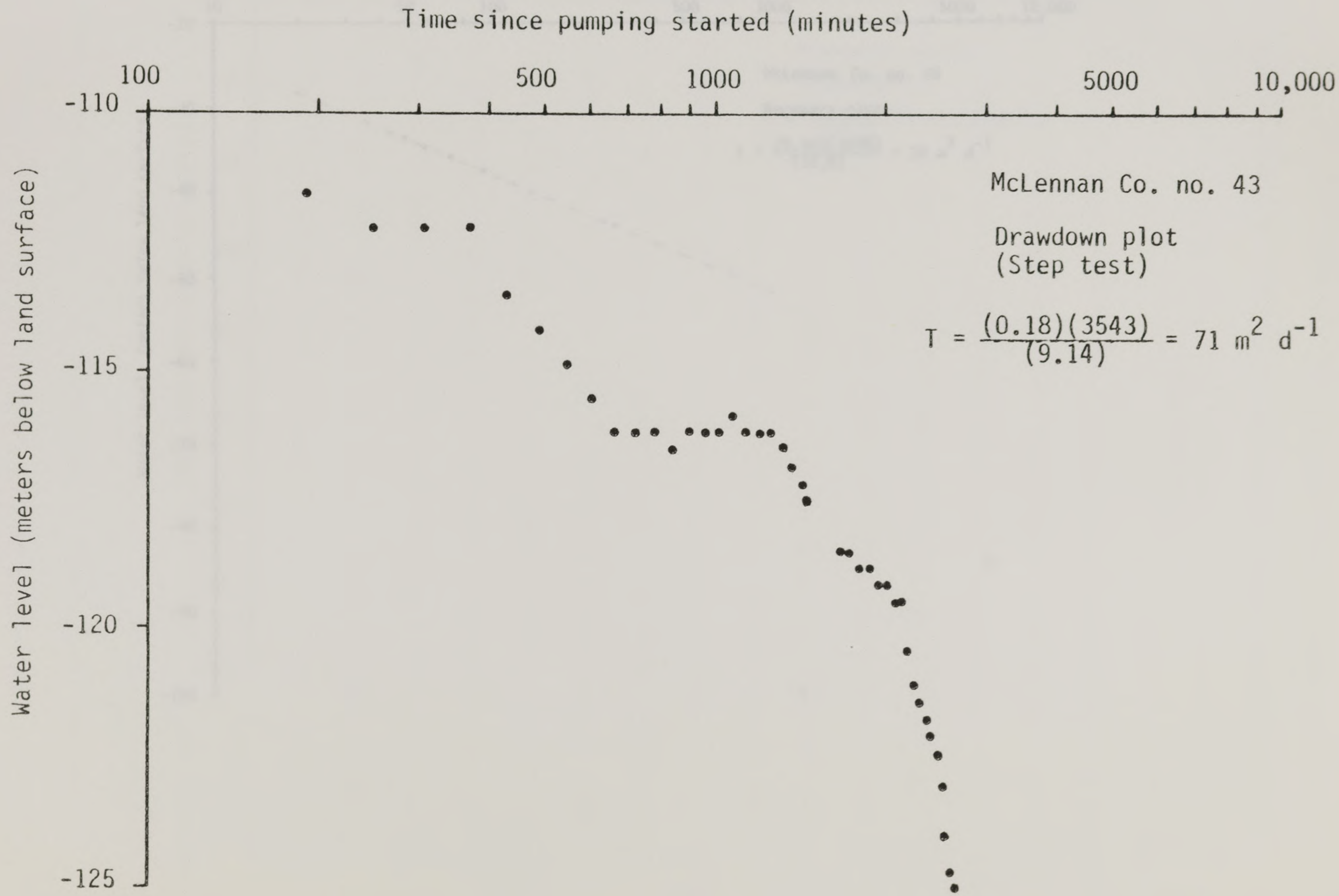


Bell Co. no. 27
Recovery plot
$T = \frac{(0.18)(2927)}{(0.92)} = 582\ m^2\ d^{-1}$
t/t'
5
10
50
100
500
1000
s' (meters)
1
2
3

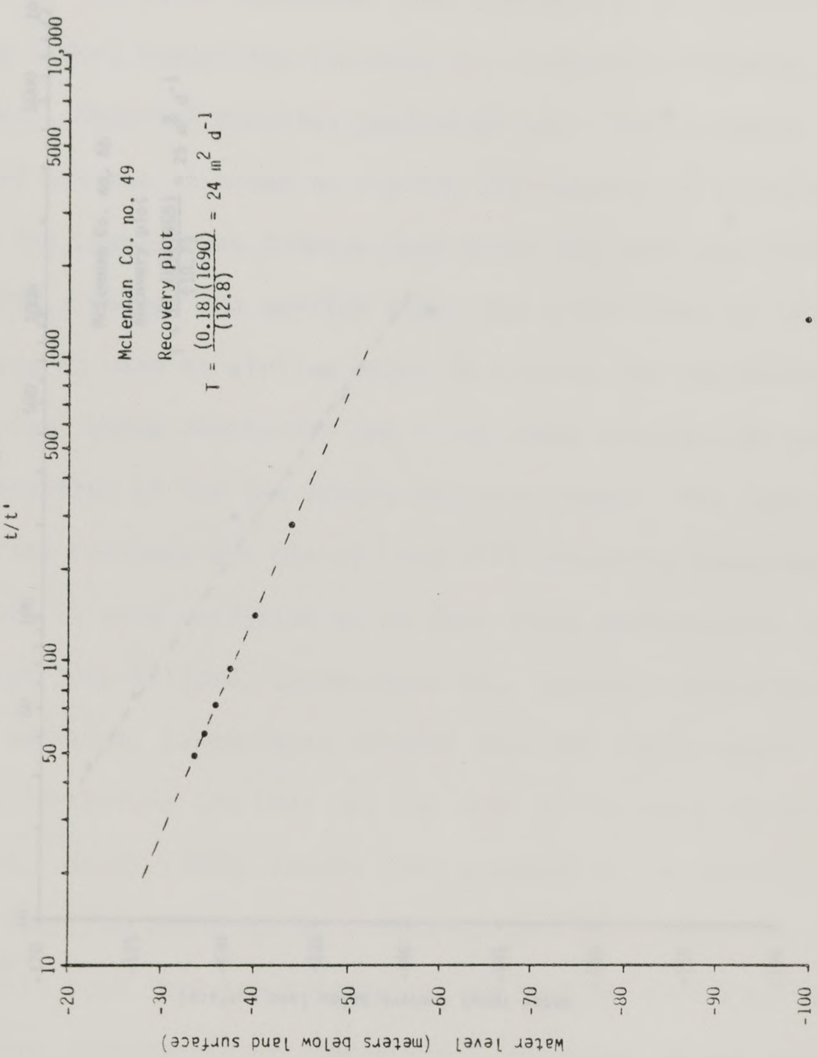

Bell Co. no. 37
Recovery plot
$T = \frac{(0.18)(654)}{(1.25)} = 96\ m^2\ d^{-1}$
t/t'
10
50
100
500
1000
s' (meters)
2
3
4

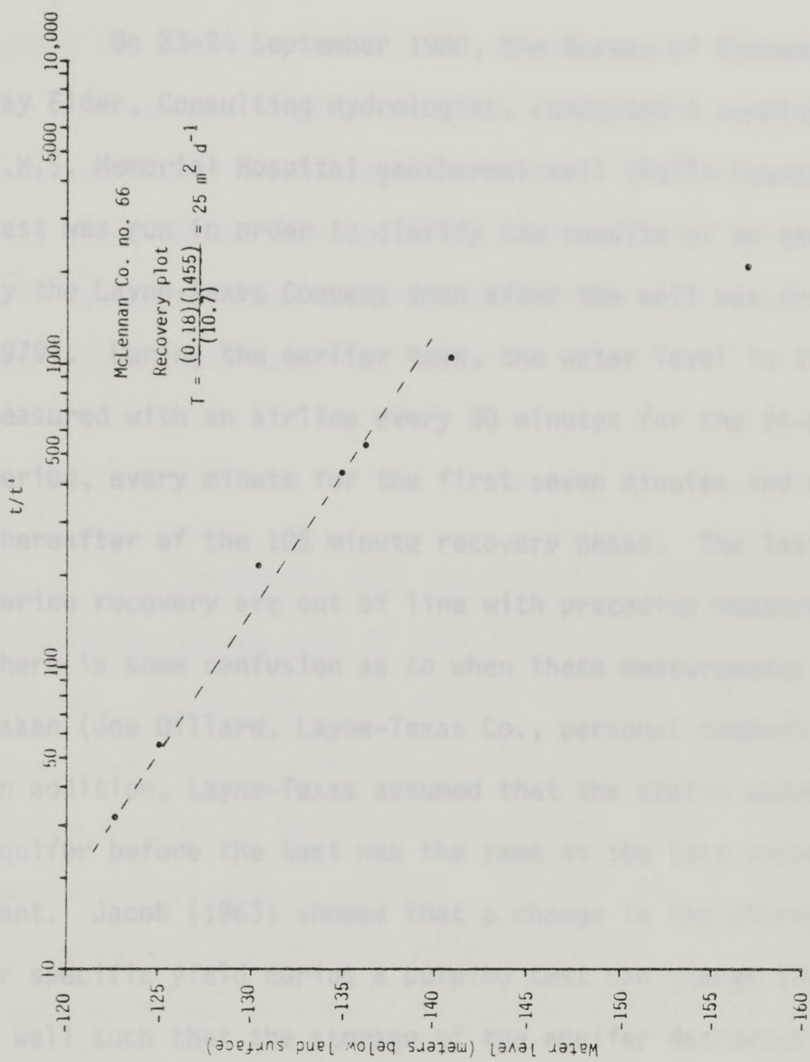

t/t'
10
50
100
200
300
400
5.5
6.0
6.5
7.0
7.5
s' (meters)
Bell Co. no. 40
Recovery plot
$T = \frac{(0.18)(801)}{(1.22)} = 72\ m^2\ d^{-1}$


t/t'
1
5
10
50
100
500
+5
0
-5
-10
-15
Water level relative to land surface (meters)
(Points based on head on orifice)
McLennan Co. no. 14
Recovery plot
T = (0.18)(2780) / (6.55) log10 (200)/(110) = 20 m2 d-1



Time since pumping started (minutes)
100
500
1000
5000
10,000
-110
-115
-120
-125
Water level (meters below land surface)
McLennan Co. no. 43
Drawdown plot
(Step test)
$T = \frac{(0.18)(3543)}{(9.14)} = 71\ m^2\ d^{-1}$


t/t'
10
50
100
500
1000
5000
10,000
McLennan Co. no. 49
Recovery plot
T = (0.18)(1690) / (12.8) = 24 m2 d-1
-20
-30
-40
-50
-60
-70
-80
-90
-100
Water level (meters below land surface)


McLennan Co. no. 66
Recovery plot
T = (0.18)(1455)/(10.7) = 25 m2 d-1
t/t'
10
50
100
500
1000
5000
10,000
Water level (meters below land surface)
-120
-125
-130
-135
-140
-145
-150
-155
-160

APPENDIX V: Results of Pumping Test, T.H.S. Memorial Hospital Geothermal Well, Marlin, Texas

Introduction

On 23-24 September 1980, the Bureau of Economic Geology and Ray Elder, Consulting Hydrologist, conducted a pumping test of the T.H.S. Memorial Hospital geothermal well (Falls County no. 35). This test was run in order to clarify the results of an earlier test run by the Layne-Texas Company soon after the well was drilled (27-28 July 1979). During the earlier test, the water level in the well was measured with an airline every 30 minutes for the 24-hour pumping period, every minute for the first seven minutes and every five minutes thereafter of the 105 minute recovery phase. The last measurements during recovery are out of line with preceding measurements, and there is some confusion as to when these measurements actually were taken (Joe Dillard, Layne-Texas Co., personal communication, 1980). In addition, Layne-Texas assumed that the static water level in the aquifer before the test was the same as the last recovery measurement. Jacob (1963) showed that a change in the storage coefficient or specific yield during a pumping test can change the recovery of a well such that the storage of the aquifer decreases during the test, either permanently or temporarily, and water levels during recovery are higher than expected. If the change in storage is temporary, the water level will continue to recover slowly by decreasing until the static water level is reached. Whether or not the aquifer does recover completely is of interest when considering large and long-term withdrawal of water from the aquifer, as is the case with the geothermal well in Marlin. As shown below, the static water level before the 1980 pumping test of the geothermal well was 1.8 m below the land surface, whereas the static water level assumed by Layne-Texas was 4.5 m above the land surface. Because of these uncertainties about the earlier test, and because it was possible that some well development had occurred during that test, the geothermal well was retested, as described below.

Method

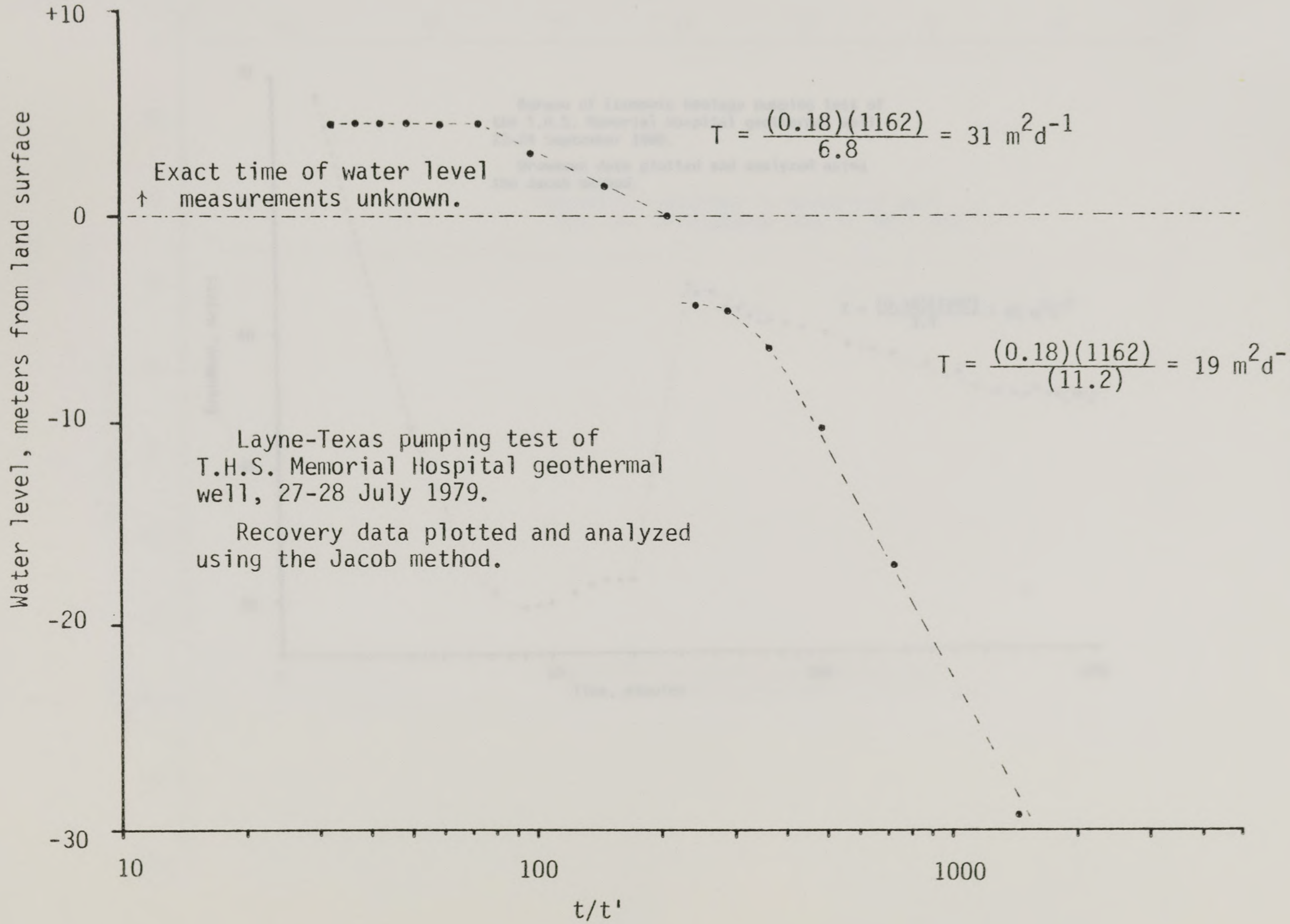
The geothermal well was pumped for approximately 18 hours at a weighted-average rate of 1192 liters per minute (315 gallons per minute). During the first part of the test, water-level measurements were taken with an electric sounded (E-line) until that instrument became tangled in the pumping equipment. After that time, water levels were measured with an airline. The well was allowed to recover for approximately four minutes before it began flowing and measurements could no longer be taken. Because of equipment problems, the plan of removing the pump and placing a pressure gage on the well to record the remainder of the recovery was aborted. The salient data pertaining to water-level measurements, time of pumping and recovery, and pumping rates are listed at the end of this appendix.

Two other wells in Marlin were observed during the pumping of the Marlin well because records at the TDWR indicated they were screened, at least in part, in the Hosston/Cotton Valley hydrogeologic unit. These two wells are the well at the Chamber of Commerce Pavillion (no. 38) and the Central Texas Savings well (no. 37). The latter well, which has been shut-in since 1945 or sometime after 1967 (dates from two different sources in TDWR files), was measured using a pressure gage accurate to 0.1 psig (approximately 0.07 m). The former well flows into a community drinking fountain and is now being used to heat the Chamber of Commerce building. This well was measured using a gage accurate to about 0.3 m. Well no. 38 showed no response during the pumping test; well no. 37 showed a slight response, probably due to changes in air temperature. Pertinent data are shown at the end of this appendix. These wells are apparently no longer hydrologically connected to the Hosston/Cotton Valley hydrogeologic unit.

Results

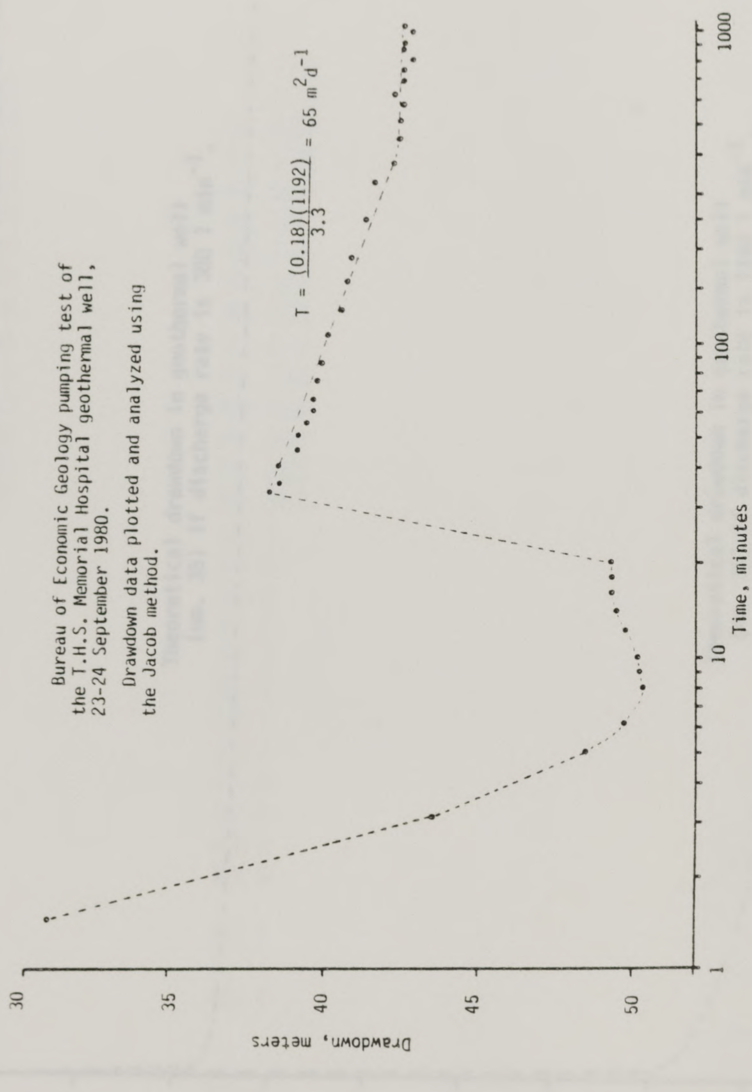
The transmissivity calculated from a Jacob plot of the drawdown part of the pumping test is significantly higher than that calculated from the test run by Layne-Texas Co. (94 m^2d^{-1} versus 31 m^2d^{-1}; see plots below). This may be the result of increased well development or of a more accurate static-water-level measurement.

Using the transmissivity calculated from the pumping test, the ability of the Hosston/Cotton Valley to provide water is aptly demonstrated with water levels projected for withdrawal over a period of time. Shown below is a curve using a withdrawal rate of about 380 liters per minute for a five-year period. The maximum drawdown at the well would be 25 m using these projections. Also shown is the theoretical drawdown if the withdrawal rate is 1190 liters per minute. After about 10 years, the drawdown would be more than 80 m using this higher discharge rate.

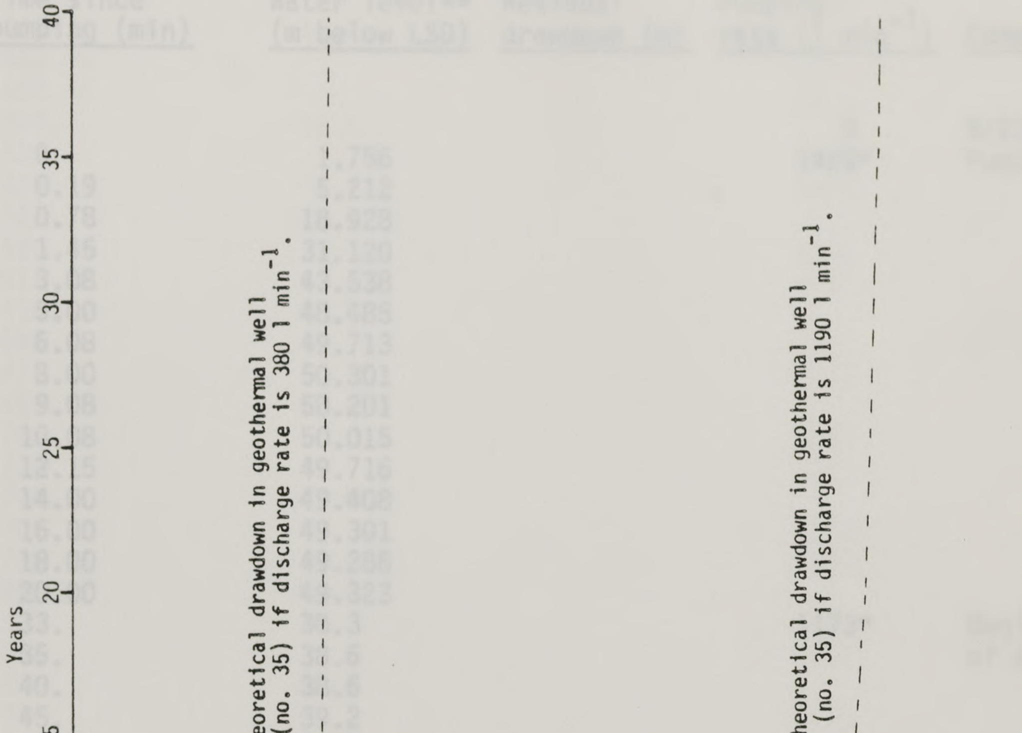


Layne-Texas pumping test of T.H.S. Memorial Hospital geothermal well, 27-28 July 1979.

Recovery data plotted and analyzed using the Jacob method.



Bureau of Economic Geology pumping test of the T.H.S. Memorial Hospital geothermal well, 23-24 September 1980.
Drawdown data plotted and analyzed using the Jacob method.
T = $\frac{(0.18)(1192)}{3.3}$ = 65 m^2d^{-1}
Drawdown, meters
30
35
40
45
50
Time, minutes
1
10
100
1000


Years
Drawdown (meters)
0
5
10
15
20
25
30
35
40
0
10
20
30
40
50
60
70
80
90
100
Theoretical drawdown in geothermal well (no. 35) if discharge rate is 380 l min^{-1}.
Theoretical drawdown in geothermal well (no. 35) if discharge rate is 1190 l min^{-1}.

Pumping Test Data

Time since pumping (min)	Water level** (m below LSD)	Residual drawdown (m)	Pumping rate ($l\ min^{-1}$)	Comments
			0	9/23/80 SWL
0	1.756		1420*	Pump on
0.19	5.212			
0.78	18.928			
1.45	31.120			
3.08	43.538			
5.00	48.485			
6.08	49.713			
8.00	50.301			
9.08	50.201			
10.08	50.015			
12.15	49.716			
14.00	49.408			
16.00	49.301			
18.00	49.286			
20.00	49.323			
33.	38.3		1173*	Begin use of airline.
35.	38.6			
40.	38.6			
45.	39.2			
50.	39.2			
55.	39.5			
60.	39.7			
65.	39.7			
75.	39.8			
85.	40.0		1192*	
105.	40.1		1192	
125.	40.6		1208*	
135			1211	
157.5	40.7			
165			1208	
185.	40.9			
195			1208	
225			1173	
246.	41.3			
255			1136	
315			1136	
321.	41.6			
345			1211	
371.	42.2			
375			1211	Train, t= 376-386

Time since pumping (min)	Water level (m below LSD)	Residual drawdown (m)	Pumping rate (l min^{-1})	Comments
405			1211	
435			1211	
445.	42.4			
465			1211	
495			1211	
504.	42.4			
525			1211	
555			1173	
567.	42.6			
585			1211	
615			1192	
616.	42.2			Train, t=
645			1211	653-663
675			1211	
680.	42.6			
705			1192	
735			1173	
740.	42.6			
765			1173	
795			1192	
800.	42.9			
825			1173	
855			1192	
860.	42.6			
885			1173	
915			1173	
920.	42.6			
945			1173	
975			1173	
980.	42.9		1173*	Train, t=
1005			1173	987-997,
1035			1192	1008-1018
1040.	42.6			
1065			1211	
1095			1173	
1115.			0	Pump off
1115.12		34.7		
1115.43		26.5		
1115.63		21.6		
1115.83		18.8		
1116.00		16.7		
1116.20		14.3		
1116.40		12.8		
1116.58		11.2		
1116.83		9.4		
1117.00		8.2		

Time since pumping (min)	Water level (m below LSD)	Residual drawdown (m)	Pumping rate ($l\ min^{-1}$)	Comments
1117.15		7.0		
1117.37		6.0		
1117.63		4.5		
1117.92		3.6		
1118.20		2.7		
1118.62		2.1		
1118.80		1.5		
1119.03		0.9		
				Well flowing

* All pumping rates reported by Tom Smith Pump Company except those marked with * which were measured by Ray Elder and BEG personnel.

**Data for pumping well, T.H.S. Memorial Hospital geothermal well, Marlin (well no. 35).

Time (min)	Barometric pressure*	Depth to water (m)**	Comments
+45	0.9816		9/23/80 (pre-test)
0		+37.9	Pumping well on.
1		+37.9	
20		+37.9	
40		+37.9	
135	0.9807	+37.9	
185		+37.9	
200		+37.9	
215		+37.9	
255		+37.8	
315	0.9817		
327		+37.7	
381		+37.7	
452		+37.7	
495	0.9821		
509		+37.6	9/24/80
571		+37.6	
628		+37.6	
675	0.9816		
690		+37.6	
750		+37.7	
810		+37.7	
855	0.9819		
870		+37.7	
930		+37.7	
990		+37.7	
1000		+37.6	
1035	0.9832		
1050		+37.6	
1115		+37.6	Pumping well off.

*Barometric pressure in atmospheres; data collected by the National Weather Service and provided by Tom Larkin, Weather Modification Section, Texas Department of Water Resources.

**Data gathered for observation well, Central Texas Savings, Marlin (well no. 37).

APPENDIX VI: Chemical analyses of ground-water samples collected during October, 1981, and cross reference to well numbers used in water chemistry discussion.

Appendix VIA: Chemical analyses, excluding stable isotope analyses.

Well No.	Depth (km)	Temp. (°C)	pH	Ca[1]	Mg[1]	Na[1]	K[1]	SO_4[1]	Cl[1]	Alk.[2]	F[1]	SiO_2[1]	H_2S[1]	Total Dissolved Solids[1]
						BELL COUNTY								
10	0.378	28.5	8.5	9.0	3.3	380	3.0	170	225	454	2.0	33.2	---	1100
						FALLS COUNTY								
4	0.764	37.0	8.4	4.9	1.3	310	2.2	182	69.5	466	2.6	23.3	---	1080
32	3.027	---	6.25	20.8	0.1	1.5	0.7	1.0	10.5	---	0.10	2.4	1.7	80
35[3]	1.142	68.9	7.33	278	35	815	---	2256	87	168	0.8	40	---	3680
41	1.074	67.0	7.3	220	35.0	1350	20.0	2700	250	206	1.7	33.7	1.0	4940
43	1.123	61.0	7.4	16.9	3.1	250	7.3	150	62.9	448	3.1	36.4	1.0	700
44	0.915	40.0	8.0	14.0	3.3	300	4.0	300	60.7	412	1.6	68.3	---	1000
						LIMESTONE COUNTY								
44	3.922	---	4.7	8450	750	42,750	1430	20.0	78,700	---	0.1	165	---	134,600
86	2.462	---	5.6	12,800	875	60,500	1300	315	100,000	---	0.4	39.8	1.0	180,000
93	3.428	---	---	10,300	1100	45,900	1300	15.0	87,400	---	0.6	25.7	---	148,200
						McLENNAN COUNTY								
4	0.841	35.0	8.5	13.1	3.6	530	4.5	89.0	575	414	1.7	19.5	1.0	1400
9	0.912	46.0	8.1	3.4	0.5	290	2.5	110	70.0	506	2.0	29.0	---	1000

Appendix VIA, continued.

Well No.	Depth (km)	Temp. (°C)	pH	Ca[1]	Mg[1]	Na[1]	K[1]	SO_4[1]	Cl[1]	Alk.[2]	F[1]	SiO_2[1]	H_2S[1]	Total Dissolved Solids[1]
23	0.430	36.0	8.4	3.6	1.3	330	2.1	110	180	489	2.2	17.2	<1.0	920
77	1.043	62.5	7.2	85.0	12.0	245	10.3	480	60.3	339	2.0	33.7	<1.0	1300
82	0.792	47.0	8.2	7.1	1.7	360	3.2	83.0	283	415	1.7	25.1	<1.0	1300
94	0.397	26.0	8.6	4.2	1.6	340	2.1	77.0	305	450	1.4	15.8	1.4	1100
MILAM COUNTY														
1	1.005	52.0	7.5	57.0	15.2	525	12.6	800	200	323	2.0	28.9	<1.0	1800
ROBERTSON COUNTY														
24[4]	4.187	---	6.1	93.0	5.8	320	16.2	27.0	550	---	0.1	29.0	<1.0	1200
25	3.518	---	5.7	5840	412	48,750	1815	370	78,600	---	0.5	88.5	<1.0	133,700

[1]Reported in mgl^{-1}.
[2]Bicarbonate alkalinity, reported in mgl^{-1}.
[3]Reported by Layne-Texas Co. Sample collected from drill pipe, 18 June 1979. Alkalinity and pH were probably determined in the laboratory. Sodium plus potassium reported as sodium.
[4]Sample from the Cotton Valley limestone, not the Cotton Valley clastics.

Appendix VIB: Stable isotope analyses.

Well No.	$\delta^{13}C$[1]	$\delta^{18}O$[1]
	BELL COUNTY	
10	-7.95	-5.37
	FALLS COUNTY	
4	-8.6	-5.96
43	-11.7	-5.63
	LIMESTONE COUNTY	
44	-11.81	+1.99
86	-12.2	+3.43
93	-2.13	
	McLENNAN COUNTY	
4	-9.2	-5.64
9	-9.7	-5.93
23	-9.65	-6.61
77	-10.13	-5.38
94	-8.49	-5.30
	MILAM COUNTY	
1	-11.7	-5.48
	ROBERTSON COUNTY	
24[2]	+3.00	+5.28
25	-17.5	+6.14

[1]Reported in parts per mil.
[2]Sample from Cotton Valley limestone, not Cotton Valley clastics.

Appendix VIC: Cross-reference to water wells with chemical analyses excluding those already referenced in Appendix II. Well numbers listed below correspond to those numbers underlined on Figure 40. These numbers do not correspond to BEG Low-Temperature Geothermal project well numbering system (see introduction to Appendix II).

No.	TDWR No.	No.	TDWR No.
BELL COUNTY		McLENNAN COUNTY	
1	40-58-801	1	40-16-501
2	58-05-402	2	40-16-801
3	58-05-202	3	40-22-801
4	40-61-505	4	40-24-702
5	40-61-501	5	40-31-201
6	40-61-106	6	40-39-102
7	40-53-705	7	40-46-101
8	40-53-405	8	40-16-701
9	40-61-301		
10	40-54-701		

Appendix VID: List of water wells which are probably producing from the Glen Rose Formation as well as the Hosston/Cotton Valley, as deduced from chemical properties of the water and/or hydrological properties.

County	TDWR No.
Falls	39-41-602
	39-41-604
McLennan	40-16-801
	40-22-802
	40-37-901
	40-46-401

REFERENCES

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